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ADAPTABLE THERMAL STORAGE FAÇADE DESIGN TO OPTIMIZE ENERGY USE

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ADAPTABLE THERMAL STORAGE FAÇADE DESIGN TO OPTIMIZE ENERGY USE

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DEDICATION

To my parents and my boyfriend,
always close, even 6676 *kilometres away ...*

ACKNOWLEDGEMENTS

My first thought goes to my wonderful family, especially to my mother and father, who makes my dreams become reality, for 23 years.
I would say thank you to my boyfriend who supports me all around the globe and to my "canadian family" in Mississauga, re-met after 13 years, who makes me feel at home.
I would like to express my gratitude to all those people who view the diversity as a strength.
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RÉSUMÉ

Les changements récents liés à la conception et au fonctionnement du système électrique ont créé la nécessité d'avoir une demande énergétique plus flexible. L'objectif de ce mémoire est de proposer des méthodes pour minimiser le coût de la consommation énergétique de l'utilisateur dans une ville intelligente. La démarche mise en oeuvre utilise le flux thermique dans une unité résidentielle / commerciale / institutionnelle faisant partie d'un grand bâtiment. Ce flux est composé de l'énergie que l'unité doit acheter au réseau électrique et de l'énergie dépendant des caractéristiques du bâtiment et des activités à l'intérieur : l'orientation de la façade, l'emplacement du bâtiment, le type de construction, la latitude de la ville et les conditions météorologiques.

Ce mémoire vise à intégrer tous ces facteurs pour améliorer l'efficacité énergétique des bâtiments et, de cette façon, de toute une ville ou district. Plus précisément, cette recherche se concentre sur la première couche d'une système multi-couches, soit : l'unité. Tous les modèles proposés dans la présente étude peuvent gérer différents types d'unités, i.e., une habitation, un bureau, une classe, etc...

Nous présentons trois modèles qui minimisent le coût final et la consommation d'électricité d'une unité ; pour faire cela, nous n'utilisons pas des dispositifs additionnels, tels les batteries, mais nous nous appuyons sur la structure même du bâtiment.

Tout d'abord, nous montrons comment caractériser chaque orientation des unités, grâce au calcul des gains d'énergie solaire. Ensuite, nous présentons le modèle standard qui considère le chauffage, le refroidissement et l'éclairage d'une unité. Enfin, nous modélisons une technologie de façade avec une double peau en vue d'améliorer le phénomène naturel du stockage thermique d'une unité. Nous appelons ce second modèle ''Passive house model". Par la suite, nous présentons une amélioration du système pour contrôler les gains solaires : la technologie de façade dynamique. Ce dernier modèle permet de réduire les pics de consommation d'électricité, et présente des avantages pour le fournisseur d'énergie.

Nous validons les modèles en comparant le système SM avec SIMEB energy software. Pour cette raison, nous adaptons le modèle SM: il agira seulement pour reproduire le profil de consommation d'énergie d'une unité (pas d'optimisation). Nous validions une unité avec caractéristiques similaires pour chaque orientation, pendant l'hiver et l'été. Ensuite, nous comparons les profiles de consommation obtenues avec le modèl SM et SIMEB. Nous utilisons cette calibration aussi pour fixer les paramètres des modèles.

Nous présentons les résultats et discutons de l'importance de l'orientation de l'unité, des avantages de la technologie Passive house, de la variation du coût par rapport à la température

à l’intérieur de l’unité et des avantages d’avoir une façade dynamique.

ABSTRACT

The recent changes in the design and operation of power systems have created the need for a more flexible energy demand. Because of that, the goal of this work is to propose an optimization framework to minimize the user cost in a smart building. This approach profits from the thermal flux inside of a residential/commercial/institutional unit which belongs to a large building. This flux is composed by energy that has to be bought from the electric grid and by the energy amount that depends on the building's features and activities inside: façades' orientation, building's location, construction technology, city's latitude and weather condition.

This study aims to manage all these factors to improve the energy efficiency of the building and, in this way, of an entire district or city. More precisely, we focus on the first layer of the Multilayer System: the unit. All the models proposed in this paper can manage different types of units, such as household, office room, classroom etc.. and having multiple layout structures (row houses, duplex houses etc...).

We present three models that minimize the final energy cost and consumption of the unit; to do that, we will not use additional tools as home batteries, but we benefit from the building's structure itself.

First of all, we show how we characterize each façade orientation by calculating its specific solar gains values. After that, we present the standard model that accounts for the heating, cooling and lighting behaviour of the unit. Next, we integrate a double skin façade, with the aim of improving the natural heat storage behaviour of the unit and we propose the "passive house model". Subsequently, a further improvement of the system is introduced into the study case, with the aim of controlling solar gains: the dynamic façade technology. This final version of the technology allows to reduce the electricity demand peak, reporting benefits for the customer and the grid operator.

We validate the models by comparing the SM system to SIMEB energy software. To do that, we adjust the SM model to make it act as load calculator (without optimization). We run a similar unit per each orientation, during winter and summer scenarios and we compare the energy consumption obtained by the SM model to SIMEB. This validation is used also to calibrate the input parameters of the three models.

We present computational results for our final model that show the importance of the unit's orientation, the advantages of the passive house technology, the cost variation according to the temperature inside the living zone and the benefit of having a dynamic façade.

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LIST OF SYMBOLS AND ABBREVIATIONS

DYN	Dynamic Model
EMS	Energy Management System
HVAC	Heating Ventilation and Air Conditioning
PH	Passive House Model
PCM	Phase change material
SM	Standard Model
TES	Thermal Energy Storage
ZEB	Zero Energy Building
hp	Heat pump cycle
DSF	Double skin façade

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CHAPTER 1 INTRODUCTION

1.1 Premise

It is necessary to point out that the models proposed in this study *are not* energy calculators. In fact, the energy software that has been designed until now, like EnergyPlus [4], IES [5], EcoTect or SIMEB [6], are load calculators or simulators of buildings' energy behaviour. The models that we present in this work, not only calculate the energy loads of the unit, by accounting for its features and weather conditions, but they also optimize the amount and timing of loads, with the aim of minimizing both the final cost for the user and the operation cost for the utility.
Moreover, most of those calculators, as EnergyPlus, IES and EcoTect, are thought for architects and engineers, but not to be used by the consumer: their main goal consists in helping designers during the early stages of the building planning, for having an energy efficient construction at the end of the work. Furthermore, for a standard user, who has no knowledge in the field of energy buildings, it is difficult to manage mostly the totality of these software programs. In addition to that, they do not provide a direct information about the final energy cost, neither instructions for diminishing it. Instead, the models that we present in this work minimize the electricity cost in operation for the user and reduce the total energy consumption. In other words, these models have to be thought as the heart of an energy management system (EMS) of a smart home: they find the optimal energy schedule for each unit, for each time period, with the aim to minimize the electricity bill of its user. More in detail, they act on the temperature inside the unit: they find the optimal temperature, per each time period, inside the unit that minimizes the final electricity cost for the user.

1.2 The context

The need to optimize the energy consumption of our cities is already a matter of common knowledge and it is linked to both environmental reasons and socio-economic aspects. Manage such a big issue requires to start by analysing the smallest block that composes it and, most important, we have to consider all the available resources that we have. It is showed that buildings have a significant impact on the energy consumption of the city [7]. This is mostly due to their heating and cooling systems [8]; therefore, this will be the focus of this research project.
Moreover, the power systems are facing significant changes: first, the energy network is

becoming bilateral connected; not only the electricity, but also the data, have to go in two directions. This new requirement is opening the doors for what we call "Smart homes" and, consequently, "Smart cities". In fact, it is predicted [29] that by 2020, 25% of the canadian homes and 30% of the european ones will be "smart". This new type of houses make the energy demand more flexible; in this way, they are able to adapt to the dynamic prices and to the different energy resources available. To do that, they need to have an Energy Management System (EMS) that creates the optimal schedules to satisfy the energy needs of a residential/commercial/industrial unit, by shifting or reducing some loads, while minimizing cost. To reach this goal, multiple demand response programs are being developed [33].

Second, this increasing home automation, not only improves the comfort but also decreases the dependence from non renewable energies [34]. In fact, it can help to reduce the total consumption of the unit. Moreover, it has been showed by Saad al-sumaiti et al. [34] that the 41% of the energy consumption in U.S. is actually unnecessary and it is caused by the improper control of the building loads. Not only the user, but also the environment and the Utility will benefit from better managing the energy needs. The possibility to predict the energy needs, helps not only the user to be more aware about the consequences of his habits, but also the building operators and the Utility. The user's behaviour is not the only factor that has impact on the consumption: the building design, together with the location, have a great impact too. This last issue is fundamental to understand the reason behind this study: from the building operator's point of view, being aware about the amount and the timing of its users' energy consumption, means to be able to plan optimized generation schedule. In this way, he can organize his demand response market toward the users' and the producers' sides. Achieving such a goal requires to analyse in detail the thermal flux inside the unit, by accounting for its orientation, the weather, the technical features of the building envelop and the habits of the user living there. In fact, we will see in the next chapters that all those aspects have an important impact on both the final costs and the consumption.

Third, nowadays the renewable energy resources play an important role in the research on energy. When we talk about renewable energy resources, there are two main topics that come out: their intermittent behaviour and the decentralized production in the energy network. Because of their dependence on a natural resource, it often happens that the demand of energy does not meet the timing of the production, which makes costly to satisfy the demand. Furthermore, with the spread of photovoltaic panels, solar water panels and other types of local energy production, the power grid has to deal with, not only the bilateral direction of data and energy, but also with a lot of small producers scattered throughout a large territory. Moreover, the renewable resources are most of the time difficult to predict. As an example, during a cloudy day, the solar gains will lose almost totally their direct ray component. It means that the building energy management system has two choices: first, it can use other resources or forego some energy loads, second, it can store some solar energy during the surplus period and benefit from that when it needs to. For the two options, it is necessary to consider a storage and, in general, to design the building as an integrated connected system. Currently, the energy storage is being in the spotlight for renewable energy researchers; they are studying the materials it is designed with, its impact on the society and in which way the energy is stored more efficiently; indeed an home storage can accumulate energy in the form of electricity, like the lithium battery (see Figure 1.1) or in the form of heat (see Figure 1.2 and 1.3), where the size of this last type can vary considerably, according to the thermal capacity of the tank and the users' needs. There are still some important limits to overcome, such as the cost related to the battery's initial investment and the necessity to re-buy it at the end of its life cycle. In fact, it turns out to be difficult for a family to buy their own local battery. In addition to that, also the large physical space that the storage, especially the heat storage, requires, can make the concept even more difficult to implement. For that reason, we are going to propose an apparatus which is integrated into the building, whose price consists only in the initial construction cost and the ordinary maintenance and can be shared among several owners.

Neverthless, implementing a storage device is not sufficient. In this study we propose the analysis and the optimization of the energy flux inside the building. We focus on the difference among the dwellings of the same building, with the aim to benefit from that. In particular, we account for the different orientations and solar angles of each apartment. Because of that, the solar gains will prove to have the key role in the energy issue: they depend on the orientation of the unit and on the technical features of the building; in other words they are connected to both the local external conditions and to the ability of the structure to capture and conserve the energy derived from sun rays. Thinking in this way, it is worth to consider the energy from the sun as a renewable resource for the winter study case: we do not necessarily need particular tools to benefit from the sun (i.e solar panels). Instead, it can be done by using the thermal mass of the structure itself. In fact, the heat from the sun can be used to passively warm the living zone during winter. This will be showed in the standard model (SM). Sometimes this additional energy can be undesirable, such as summer time or even in winter, during the middle of the day. Accordingly, we will propose a second and third models, that is what we have called "Passive house" (PH) and "Dynamic façade" respectively, as an improvement of a standard house (SM).

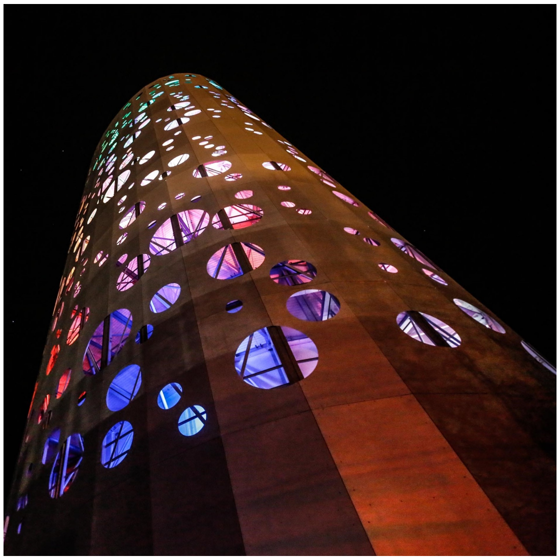

Figure 1.2 Thermal energy storage tower, Bozen-Bolzano, Italy (Bartleby08, 2017)

Figure 1.3 Home heat storage for solar water heater, Mendoza, Argentina (Cachogaray, 2010)

The three models proposed in this work are characterized by an high energy efficiency which is due to their low consumption. In the literature, they refer to this kind of building as "Zero energy buildings" (ZEB). More in detail, it took different names according to the country: it is called "Passivehaus" in Germany, "Zero energy home" in the United States, "Maison autonome en énergie" in France and "Green building" in Canada, England and United States. Nevertheless, after the European Directive (2010/31/ UE (EPBD)), all these names merged into "ZEB". The idea behind those buildings is similar but not exactly the same and the difference among them is often confused. Filippi and his collaborators [53] suggest the following definitions: the "Passivehaus" focuses on the improvement of solar gains and it is characterized by a consumption for heating which is lower than 15 kWh/m^2year; the "Maison autonome en énergie" refers to a building

Figure 1.1 Home lithium battery: Powerwall, Tesla (Tesla Motors, 2016)

off - grid, which is energetically autonomous; the “Green building” is a structure whose criteria respect green standard (for example the LEED); the “Zero energy home” is referred to a building which can be connected or not to the grid and it accounts for the total yearly consumption (not only heating). This idea of “smart design” started to spread during the 60s - 70s in California and now it has a key role in building energy field. It is possible to look at the ZEB by adopting different points of view; because of that, we find several names in the Literature: “net Zero Source Energy Building”, “net Zero Site Energy Building”, “net Zero Energy Cost Building”, “net Zero Emission Building” and “nearly net Zero Energy Building”. All of them have the goal to reach a balance equal to zero. The “net Zero Source Energy Building” is characterized by having the amount of renewable energy produced and bought by the building equal to its consumption. The “net Zero Site Energy Building” has only the renewable energy produced equal to its consumption. The “net Zero Energy Cost Building” accounts, on one side, for the incentives of the local renewable production, on the other side for the price of the building’s consumption. The “net Zero Emission Building” has its equivalent CO2 of renewable energy produced equal to the amount of CO2 emitted. Finally, the “nearly net Zero Energy Building” aims to minimize both the cost and the consumption. This last building, called “nnZEB” is well described in the European Directive 2010/31/ UE (EPBD); moreover, the EPBD declares that all the buildings have to respect the nnZEB criteria before the 31^{th} of December 2020 and all the new buildings have to be design as the nnZEB by the 31^{th} of December 2018. Some researchers have already started to study the topic in a larger scale: the net zero energy neighbourhood, where the net of energy is accounted by considering the integration different types of buildings.

Taking in account all these aspects, we have designed the building models presented in this work. All those buildings have some features in common. In fact, to significantly reduce the net energy demand, we cannot think to solely add some renewable local productions. The first step to follow to obtain a Passive building is to improve the technical features of the construction itself, with the aim of reducing as much as possible, the energy it demands: its insulation (walls, windows, roof and basement), its draft-proofing envelope, its appliances, its air conditioning and lighting systems, all have to be very efficient. The second step consists in adding and integrating the renewable energy resources into the building: in other words, the Passive house is a designing process, more than a product and its realization starts from the first preliminary project.

To summarize, we tackle the three changes in the energy field, discussed above: the smart power grid, the user’s behaviour and the renewable energy integration. We propose a solution made up by the connection of three main topics: the energy storage, the solar gains analysis and the ZEB design. The result of this work is represented by three models: the Standard house (SM), the Passive house (PH) and the Passive house with dynamic façade (Dyn). All of them represent a mathematical optimization technique applied to physical system to improve its energy efficiency. More in detail, we are going to merge both environmental and Utility's needs to propose a solution for the well known problem of reducing the fluctuation in energy demand of a city that makes challenging for the utilities to integrate efficiently renewable energy resources. Furthermore, also the users will benefit: the heat storage, the passive house and the dynamic façade, make a significant cost reduction for users and better control on demand fluctuation for utilities.

1.3 The Multilayer system

We can identify three key-concept that nowadays are leading the energy field: each approach proposed has to be *efficient, renewable and smart*; consequently, we have built our models following this philosophy.
Thinking at the full scale of a city district, we consider a behaviour "efficient" if it facilitates the balance between demand and production. In fact, this requirement brings benefit to both the users and utility sides, because it reduces the operation cost and keeps the power grid secure. To achieve this goal, from one side, the fluctuation of the demand has to be reduced, on the other side, the production has to become more flexible and dynamic. In other words, we need to account for the dynamic boundary conditions and playing with timing and storage, by shifting or deleting loads. Those boundary conditions are different not only for each building of the district, but also for each unit of a building. Consequently, we designed what we have called "Multilayer system", which represents a way to manage a large problem by deconstructing it in three smaller sub-problems that we call "layers". More in detail, it is composed by three layers arranged in a sort of matrioska, as showed in Figure 1.4. The layer 1, which is the smallest and the closest to the user, is the one we are going to present in this study: the unit. It can be allocated, as we said, for residential, commercial or institutional uses.In this thesis we present the study case of a residential unit. In fact, it has been observed that residential buildings have the highest impact on the energy consumption related to buildings. For instance, in 2011 40% of total US primary energy consumption was reserved to buildings. From this amount, 54% was consumed by the only residential sector [9]. Several units together, compose the building that is the layer 2 in our system; according to the same way of thinking, several buildings make up the city district, the largest level that is the layer 3. Each layer is characterized by an optimization problem that always makes the demand meeting the production in the most efficient way: it finds the optimal amount and timing of the energy load as results (output), after that, this load becomes the input

parameters for the next layer (Figure 1.5). As mentioned before, this research thesis will only focus on the development of the first layer.

Figure 1.4 Multilayer System scheme

The second key-concept is represented by renewable energy resources. As we mentioned, there are two main issues to account for when we deal with them: first, they have to be affordable for a common family, from the economical and operational point of views; even the smartest technology will never spread if it is too expensive. Second, renewable energy resources have to be integrated into the system; in that way, each of which can strengthen the other. Considering this, we analysed how to integrate renewable energies into the Multylayer system. In fact, for the Layer 1, we focus on the energy captured from the sun, proposing different tools to benefit from it; moreover, we assume that the totality of the energy consumption of the unit is allocated as electricity. Consequently, to minimize the final electricity cost, we use the structure of the unit itself: the external façade. By doing this, we reduce that initial cost which is always linked to the implementation of renewable resources: in this way, the system proposed becomes affordable and competitive in the energy market. Furthermore, the external façade acts as a thermal storage and insulating layer, according to the dynamic conditions of the environment; by doing this, it makes possible to coordinate renewable and non renewable energy resources while avoiding the standard home batteries, which are more expensive and require an additional space.

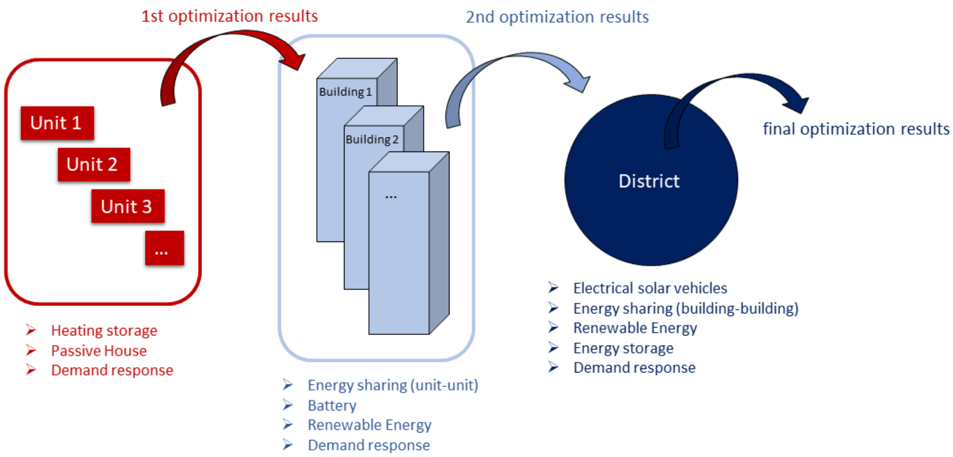

Figure 1.5 Layers' main features (Salerno, Ilaria. 2018)

To conclude, the last key concept asks the energy approach to be *smart*. The word "smart" implies that the process is automated; indeed, to manage all the requirements that we have being discussing until now, the unit (the district as well) has to be very flexible and dynamic but it is not reasonable to ask the user to do it, manually, by himself. In fact, we need a connected system where the smart power grid has the capability to manage the energy surplus and move it where it is needed. To do that, both data and the energy flow have to go in the two directions and, above all, the full system has to be user-friendly, which means that it is not only efficient but it also protects and increases the users' comfort.

Our purpose is to model a Passive house having high efficiency and meeting its demand with renewable energy, as much as possible. To improve the process, we are going to model in detail the energy flux related to each particular unit. We do this because we have reason to say that the natural capacity of the unit to store heat will prove to be helpful for cost reduction. In addition to this, different façade orientations bring different amount of solar energy contribution: this means that, if we are able to forecast the electricity requirement of all the units, according to the study of their orientation and type of use, we can allow the building operator to know exactly when and to who ask for demand response, in order to obtain the most efficient reaction.

To conclude, we can summarize the contributions of this work in five concepts. Firstly, the models proposed are cost minimizers, which can be applied also to the residential sector for all seasons. Second, we use the structure itself of the unit to store energy. We do that with the aim to increase the models' attractive for a standard family. In fact, avoiding the use of additional external tools, such as chemical batteries, could increase the affordability of these models. Third, the three models account for dynamic tariffs: the models can adapt to any tariff structure. We do that with a view to a study on demand response also for the residential sector. Fourth, we model the unit in the light of taking advantages from its uniqueness. The models can adapt to a given unit: we consider its location and the activities inside, with the aim to optimally share energy among the units in the layer 2. Finally, we significantly reduce not only final cost and power, but also the total energy consumption during the day.

CHAPTER 2 CRITICAL LITERATURE REVIEW

In this study, different research fields merge: mathematical optimization, energy storage, ZEB, and building design.

2.1 Operations research applied to energy

One of the main purposes of this study is to find the optimal schedule for a unit that minimizes the final cost without compromising comfort. The mathematical structure of our models is inspired by the "Unit Commitment" problem [41], even if the purpose behind them is different. More in detail, we look at its ramping and demand satisfaction constraints. As we said, the purpose behind the Unit commitment and our study is different: the first one focuses on the generation side while ours, on the demand side. Moreover, also the word "unit" has different meanings: for the Unit commitment, the unit represents a generator that has a production and/or a demand of energy. For our models, the unit is a physical space of a large building and it can be residential, institutional or commercial. The Unit commitment studies the optimal way to make the production matching to the demand: the main purpose consists in find which are the units to turn on/off and when to do it, to make the cost for the Utility as low as possible. As we said, the unit in the Unit commitment problem can have both a production and a demand. Our study is inspired by this idea of having a production and a demand at the same time. More in detail, we model a dwelling which has an energy production represented by the amount of energy that is produced inside, like the internal gains. Moreover, it also has a demand of energy, for example the one required for the heating system. Because of that, we bring from the Unit commitment its idea to have this two-ways connection among the units. The Unit commitment has been modelled by both linear and non linear mathematical approaches, according to the purpose of the study. For our work, we design a linear minimization problem, where both the objective function and the constraints are linear.

Until now, the operations research applied to buildings have been exploring mostly two main issues. Firstly, the objectives to reduce electricity cost and increase comfort for users, but accounting only for *static and standardized residential loads*, based on database as Desimax [10]. Secondly, different types of storage [17] to avoid to buy electricity during the most expensive hours: batteries, heat and ice [13] storage. The limits until now happens to be the fact that,concerning the residential sector, they only account one household or, if more, they are the same unit but multiplied for a certain number: in other words, there is not a differentiation among the orientations. On the other hand, we did a more detailed analysis of the dynamic environment of the building. Nevertheless, it is mainly focusing on commercial buildings. Concerning this last subject, the topic of model predictive control (MPC) is one of the most interesting. Several researchers have shown that MPC can improve the energy management in buildings. As an example, Date at al.[11] have demonstrated how MPC can reduce the energy cost and power peaks of a small commercial building over an year, even acting only on the heating system. Moreover, the research about MPC is also focusing on storage and energy management under time-of-use tariff. In our study, we keep and improve some of these topics. More in detail, all the three models face the main purpose of minimizing not only cost but also the energy consumption of the building. We are working in the light of design a passive house, which is a particular type of building having a very small energy demand. In addition to that, we keep the idea of using the unit itself to store thermal energy and we develop it. In fact, we propose what we call "Passive house model", where we analyse how a double façade can improve the capability of the unit of storing heat.

The research related to MPC is exploring also the possibility to develop a multi-level approach. In fact, one of the limits of the use of MPC, consists in the calibration of a large amount of parameters related to the building energy behaviour. Dehkordi et al. [12] showed that a hierarchical model, made up by several control layers, can solve the issue of the calibration. The authors analysed an institutional building and they demonstrated that the MPC strategy can reduce the heating and cooling cost, under time-of-use tariff. They modelled the building in three levels: building, wings and thermal zones. The optimization problem which minimizes the cost, starts at the building level. The optimal schedule is sent to the lower levels, where two negotiations happen. In the first one, the load calculated by the wings and the zones are compared. In the second one, the building previous prevision is corrected with the real loads found by the wings and the zones. The multi-level approach not only happened to behave efficiently, but also it showed to be able to account different time scales per each application, to easily incorporate uncertainty and to significantly reduce computational burden in the optimization process.

In our study, we embed the idea of tackling a large problem by facing several small problems. Nevertheless, we apply the multi-level approach to the larger scale of the city district. We implement a bottom-up model: differently from the model developed by Dehkordi et al., we design the Multilayer system starting from the smallest layer (the unit). We do that because we are interested in improving the energy management of each layer: at the unit, the building and the city levels. Another important difference between the Multilayer system and the multi-level MPC proposed by Dehkordi et al., consists in considering several energy demand profiles and types of load (not only heating and cooling).

The other subject that is not very yet studied, is the possibility to benefit from the interaction among different types of units (i.e residential, commercial and institutional) or units having different orientations. Huang et al.[42] studied the feasibility of sharing energy among 40 homes (that have all the same type of consumption), focusing on the topic of the dynamic prices and modelling an AC (Alternating Current) transmission system. They found that, from the Utility point of view, it is possible to reduce the electricity cost by 20% by sharing energy among units with a micro-grid. In this case, it is the algorithm behind the system that decides when the energy has to be shared to minimize the cost and it accounts for both space and timing.
Being able to model the thermal behaviour of the unit it is important not only for the possibility to share the surplus of energy, but also to predict its demand. It has been shown in [44] that being able to forecast the thermal behaviour of the unit, according to the dynamism of the environmental conditions (weather, sun rays, activity inside the building), can decrease the energy cost of the HVAC system of up to 28%. In fact, Fux et al. have studied a self predicted model to anticipate the thermal demand a the building; this load depends on the outside (weather) and the inside (people). In addition to that, the building modelled is a passive house with solar panels. The idea behind our study is to predict the unit's demand and to use it as input, into the home energy management system. There are two main reason to obtain this information; the first one is related to the user behaviour: if he is aware about the expense of his own home, he is more willing and capable to reduce the consumption and the cost. The second reason is more technical: the only control system acting on the HVAC may not be able to guarantee the high quality comfort that we are looking for. In fact, current HVAC systems can not perform real forecast and adapt accordingly. The HVAC may need an additional tool, as a predictive control system, which can forecast the dynamic conditions of the environment.

2.2 Energy storage

The energy storage represents another strategy to manage this dynamism of the environment. It is analysed in different scales: at the city district or at the building level. Especially in the smaller scale, it is interesting to consider different ways to store energy: as electricity or heat. For some cases, as the one analysed in this study, we have reason to say that it is more efficient to store the energy directly as heat. In fact, the energy from the sun enters the unit in the form of heat and we want to use it in this form, to warm the living zone. Instead, if we use batteries, we lose in efficiency because we need to convert that heat energy into electricity, to store it and after to convert this electricity again into heat energy to use it. For that reason, in our work we are focusing on thermal storage. Those systems have been classified by Navarro and others [43]. They show that the thermal storage technology (TES) can be a very efficient tool for buildings, above all if it is integrated into its structure. In fact, if we look at the literature, it is easy to see that there are a significant number of studies about TES but very few about its integration into the building. In other words, the subject of creating tools that can make the TES implementation easier at the design stage of the building for architects and engineers, is almost untouched. Navarro and his team, also classify the TES in three types, according to the method to store heat: sensible heat, latent heat and thermochemical storage. The first type is the most common and it stores heat by increasing the temperature of a fluid, for example air or water; the second one uses the changing phase of a material and the third one benefits from the chemical reaction among two or more elements. In our study, we will operate with the first type: sensible heat storage. We will store heat by changing the temperature of the air inside a certain reserved place (sensible storage). The energy will be transferred to the living space, using a refrigerant as heat transfer fluid.

2.3 Zero Energy Buildings (ZEB)

Until now, we have mentioned several times the Passive house, or the nZEB; they represent a growing topic in the literature. Although, to construct a building having this features is still a challenge, they are becoming more and more widespread. Several buildings that can be recognized as nZEB, have already been built throughout the world, as showed in the IEA research program “Towards Net Zero Energy Solar Buildings” [36]. Furthermore, in Canada and in Italy, some nZEB have already been designed. In Montreal, the “Abondance: le Soleil” is a residential building born from the collaboration among Studio MMA and other experts people including researchers from Polytechnique Móntreal [37]. It has obtained the LEED certification and other distinctions as “Prix d’excellence en immobilier de l’Institut de développement urbain du Québec” in 2011. On the other side of the ocean, several constructions representing different types of buildings, have been designed in Italy. For instance, the LEAF house (Life energy and future) in Ancona, built by the architect Ramazzotti in 2008, that is a zero-emission apartment and it is thought to “live as a leaf” [38]. The Zero Energy House in Felettano di Tricesimo (UD), which is a beautiful “Home Sapiens” who is capable of controlling its energy resources by its home automation system and that has been designed by the BPT Group in 2010 [39]. The primary school by the architect Vonmetz in the community of Lajon, in Sud Tirolo, that is the first Passive house school in Italy and it has obtained several distinctions, such as the “Best CasaClima” award in 2006 [40].

It have been showed that Passive houses allow their owner to both reduce costs and improve comfort (measured as level of satisfaction). By saying cost, we not only mean the final energy bill, but also the construction cost. In fact, Colcough and other researchers [45], after comparing Passive and standard houses for a total of 20 dwellings (11 of which are Passive and 9 standard), have clearly demonstrate that the passive house's construction cost it is generally cheaper than the standard one. More in detail, the study is done by considering social housing in Europe: all the data used, have been taken from the legislation and environment of Ireland and UK. They compare standard houses built by following the minimum Irish current building regulation (A3 standard) and the Passive house (A1), according to the Passive House standard. Even if the cost of the thermal envelope and windows is more expensive for the Passive (46.91 euro/m^2 more than the cost for the standard home), the one related to the ventilation and heating systems, together with the smaller construction timing, is cheaper (48.19 euro less than the standard home). Finally, the net result is that the Passive house has a construction cost which is 130 euro less than the standard one: the construction cost of the Passive is $114,862$ euros (1126.10 euro/m^2) and the standard house's one is $114,992$ euros (1127.37 euro/m^2).
It is important to stress out that the Passive house is not a technology, but it is more a building-design concept. Furthermore, there are several options to design a Passive house and it is necessary to adopt the best one for that particular conditions. Moran and others [46] have studied this topic. They analysed the Irish environment and product life cycles with the aim to explore if it is better to super-insulate the structure or to use renewable technologies for those specific conditions. They have found that focusing on minimizing the heating demand by improving the thermal transfer throughout the envelope, is the best strategy; only after that, the renewable integration can be efficiently planned. During their study, they account for the increasing of the energy prices and for the improvement of the power grid's efficiency. In other words, the approach is dynamic but it is founded on forecasting. In addition to that, they show that the biomass boiler and heat pump are the most effective renewable energy resources.

2.4 Double façade

For our models, we will implement the double skin façade concept (DSF) to the unit with the aim of obtaining the energy efficiency of a Passive house. The topic of double façade (see Figures 2.1 and 2.2) is of great interest in the literature, indeed it has been defined as one of the best solutions to efficiently manage the energy needs of a building [15]. The literature is currently focusing on the impact that DSF has on the operational energy. In

fact, it has been demonstrated that DSF can both improve the energy savings and reduce CO_2 emissions. However, there are some studies that analyse also the embodied energy perspective, as the entire life cycle of the technology. In addition to that, sometimes the variability of their results happens to be significant, especially concerning wide cavities or multi-floor configurations [15].
Researchers are analysing how DSF impacts heating, cooling, lighting and ventilation loads of a building. Moreover, an increasing appeal is related to the potential that DSF has on the subject of refurbishment in buildings. In fact, the technology happens to be cheaper and less intrusive than demolition and reconstruction.
The climate plays an important rule on the benefit that the double façade brings to the user. In fact, we want to avoid to excessively overheat the storage because we do not want to increase the losses. According to that, in certain climates, it is necessary to have a mechanical ventilation inside the double façade.

Figure 2.1 Torre Hadid, Milano, Italy (Skid22, 2017)

Figure 2.2 Torre Hadid during the construction of the double façade, Milano, Italy (Salerno, Ilaria. 2017)

As Ghaffarianhoseini and others [47] summarized in their paper, the double skin represents a thermal barrier against the not wanted climatic conditions. More in detail, by controlling the interaction between inside and outside, it reduces the unit is thermal gains and losses. There are also other important benefits in having this kind of façade: the daylighting and the glare control are better managed, due to the possibility to set the shadings in between the two skins. Additionally, it improves the acoustic insulation of the living zone and it increases the aesthetic appeal of the building (see Figure 2.3). This last point is relevant when we compute the cost of the structure: increasing the building's appeal means that also its economic value is higher and we have to consider this phenomenon when we compare the double façade to a single one. It is difficult to evaluate the appeal of a building, but it can be done by considering its high quality thermal, visual and acoustic comfort. In fact, if the dwelling achieves some criteria, it receives certifications (LEED certification, as an example) which increase its value in the market. In addition to that, it is shown that the long term cost is reduced too: thanks to the high durability and the long lasting essence of the technology, the double skin happens to be cheaper than the standard one.

The literature shows a lack in the study of the optimized overall performances: especially the summer scenario is not well analysed yet. The double façade can have different configurations according to the space in between the skins: it can be in common for the entire building surface or it can be divided in smaller parts. For our purpose, we are going to model smaller independent spaces, one per dwelling, because we want to make the system as adaptable as possible: in this way, we can consider to have units with different type of uses (i.e. office, household, restaurants), in the same building. In fact, the temperature inside the double skin, which is linked to the thermal and ventilation losses on one side and to the solar gains to the other, is something to accurately consider [16].

Figure 2.3 Palazzo Regione Lombardia, Milano, Italy (Gambini, Mauro. 2010)

2.5 Dynamic façade

The double skin technology is not the only strategy to manage and take advantages from solar gains: the dynamic façade can represent an additional efficient tool. When we talk about “dynamic façade", we mean smart automatic blinds that are able to close and open, according to the input from the environment. More in detail, the reason to adopt this technology is to meet two opposite design criteria: to increase the energy efficiency of the dwelling and to improve the visual and thermal comfort. This type of façade is increasingly being studied and used and it is common to place it in between the two skins of a double façade, with the aim to protect it from the wind and adverse weather conditions. The literature goes as well into this topic. Moreover, Konstantoglou and others [48] and Hammad et al.[24] have found that the most studied technology is motorized blinds, while other more complex ones, like the foldable façade, are not very well analysed. In fact, it has been shown that the level of complexity has a direct impact on their performance: they are less efficient if they are both too complex or too simple, because some problems start to happen during the design and installation phases. In addition to that, they show that the efficiency of the dynamic façade depends strictly on its integration with the lighting and heating/cooling systems; in other words, to obtain the best results in matter of energy and comfort, it is necessary that the automatic shadings control is connected to the temperature inside the living zone and to the amount of solar gains captured by the unit. By doing this, the overall energy saving obtained is around the 20% for the cooling consumption and the 50% for the lighting one. Furthermore, they have found that the users are more willing in adopting this technology, if there is the possibility to override the system and if its interface is simple enough. For those reasons, we have decided to propose an improvement of the Passive house modelled (chapter 5), by implementing also a dynamic façade (chapter 6) which is linked to both the heating/cooling system and the lighting.

Another way to better manage solar gains, is represented by the Phase change material (PCM). Including PCM in the models is interesting for future works. In fact, they may improve the storage capability of the units. We can think about that as a tool to increase the thermal storage capability of the walls in a dwelling; more in detail, it makes the wall acting as a latent storage. In fact, it has been shown [35] that it can bring the 57% energy saving and increase the indoor comfort.

2.6 Smart city and machine learning

Smart city planning can be the solution to the problem of rapid urbanization and growth in population. The current quality of life requires an increasing amount of energy but that quantity has a limit. To satisfy this requirement, it is necessary to design cities in a smarter way.

The literature offers many definitions of smart city; however, we prefer to describe it according to its two main features. Firstly, the city has to be flexible. By the word flexible, we mean that its energy production is able to meet the demand in a new way. In fact, the penetration of renewable sources in the energy system increases the fluctuation of the demand. Because of that, it is important that the city can "move" the energy consumption in both space and time. To do that efficiently, the system has to consider its users: their habits, their necessities and their eventual active participation to the energy network operations. Second, the elements constituting the smart city have to be resilient: in case of contingency, we want these elements to keep working efficiently or recover quickly. In other words, each element of the smart city has to be integrated into a connected network but also self-sufficient to overcome eventual problems related to power grid.

Modelling the energy system of a smart city is an interesting challenge, which is being studied by researchers. Moreover, several full-scale models of smart city districts have been developed, with the aim of conducing real test. The Nordhavn district is an interesting example of that [26]. It is a project of the EnergyLab Nordhavn, which is investigating the energy supply and consumption of a smart city. Nordhavn is a low energy district, not isolated but connected to the rest of Copenhagen. It represents a living laboratory, which includes many modern automated building systems. Nordhavn, together with the other full-scale labs in the world, demonstrates that it is possible to create a smart district.

For the purpose of our future work related to the Multilayer system, we are interested in machine learning methods to estimate the energy load of buildings. Few researchers have started studying how machine learning can offer a more general and faster methodology to consider heating and cooling loads of buildings, than mathematical methods. For instance, Ertugrul et al.[30] showed that extreme learning method (ELM) solves two issues which usually mathematical models have: it is not restricted to a particular location and it requires less technical data. Moreover, it uses linear algebra and it is faster than other machine learning methods. Few years before, Tsanas et al.[31] designed a method based on machine learning, which estimates heating and cooling loads of a building, according to its main features, such as windows size and orientation. Tsanas clearly supports machine learning has a fast and efficient way to calculate building loads. More recently, Kumar et al.[32] used the extreme machine learning method to choose in advance the best features to design buildings, with the aim to help engineers during the first phase of the project. This method has been declared by the author as the first attempt of machine learning applied to building design. We are interested in machine learning techniques to connect the layer 1 to the layer 2 of the Multilayer system. We will cluster units according to their main features, such has orientation and activity inside. We will collect their optimal energy load schedule and use it to train the model of the layer 2. Nevertheless, this subject will be studied in the future works. As mentioned previously, this work will focus on the first layer of the Multilayer system.

CHAPTER 3 ASSUMPTIONS FOR THE OPTIMIZATION MODELS

3.1 Solar gains

Solar gains are the main characters of this study: we can think about them and about internal gains (they are explained in the following chapters) as the energy that the building receives, regardless of our will: in other words, both solar gains and internal gains can help to heat the unit during winter.
The calculation related to the amount of energy coming from the sun and entering the unit, follows the ASHRAE Fundamentals Handbook, 2009 [1].
Values' names, as the calculation method, agree with the american nomenclature. In detail, the elements having subscript z or s are referred to the sun. Subscripts t and n are connected to the angle of the radiation on the surface: if it measures 90 degrees, the letter n is used, otherwise the subscript is t. Letters b, d and r refer to the type of solar irradiation: it can be, respectively, direct, diffuse or reflected. Finally, the subscript i is connected to the time period, which in our case lasts one hour. Solar gains differ according to the site, the orientation of the unit, the period of the day and the year and the technical features of windows. We assume that the sun rays passing throughout the opaque ratio of the wall are negligible, based on the ASHRAE Fundamentals Handbook. All these aspects have been considered in the following model.

Solar parameters are defined as follow:

- $\theta_{z,i}$: Solar zenit [$°C$];
- $\gamma_{s,i}$: Solar azimut [$°C$];
- $G_{bt,i}$: Direct solar irradiation on a generic surface [W/m^2];
- $G_{dt,i}$: Diffuse solar irradiation on a generic surface [W/m^2];
- $G_{rt,i}$: Solar irradiation ratio that has been reflected from the ground to the windows surface [W/m^2];
- G_{bn}: Normal direct solar irradiation on a horizontal surface [W/m^2];
- G_d: Diffuse solar irradiation on a horizontal surface [W/m^2];

The technical and physical features of the windows come after:

- θ_i: Surface zenit $[°C]$;
- γ: Surface azimut $[°C]$;
- β: Surface angle compared to the horizontal plane $[°C]$;
- IAC: Indoor attenuation coefficient [-];
- $SHGC_{b,(\theta),i}$: Solar heat gain coefficient for direct irradiation [-];
- $SHGC_d$: Solar heat gain coefficient for diffuse irradiation [-];
- ρ_g: Ground reflectance (albedo) [-]

We account for solar gains as a sum of three components:

$$q_{sol,i} = q_{cond,i} + q_{SHG,b,i} + q_{SHG,d,i} \tag{3.1}$$

where, $q_{cond,i}$ is the conductive ratio of solar rays:

$$q_{cond,i} = u_w a_w (t_{ext,i} - T_i^{int}); \tag{3.2}$$

Where T_i^{int} is the temperature inside the building and $t_{ext,i}$ is the temperature outside, per each time period i.
In a similar way, $q_{SHG,b,i}$ and $q_{SHG,d,i}$ will take into account the other two heat transfer types: the convective and radiative ones. They are related, respectively, to the direct radiation (b as beam) and the diffuse one (d as diffuse):

$$q_{SHG,b,i} = IACG_{bt,i} a_w SHGC_{b,(\theta),i} \tag{3.3}$$
$$q_{SHG,d,i} = IAC(G_{dt,i} + G_{rt,i}) a_w SHGC_d \tag{3.4}$$

From the equations above it is easy to notice the direct dependence of solar gains on both solar irradiation ($G_{bt,i}$, $G_{dt,i}$ and $G_{rt,i}$), technical features of the windows (a_w, $SHGC_{b,(\theta),i}$ and $SHGC_d$) and the environment (IAC).
More in detail, we calculate the solar irradiation incident on a particular surface in the

following way:

$$G_{bt,i} = G_{bn} \cos \theta_i \tag{3.5}$$

$$G_{dt} = G_d(\frac{1 + \cos \beta}{2}) \tag{3.6}$$

$$G_{rt,i} = \rho_g G_i(\frac{1 + \cos \beta}{2}) \tag{3.7}$$

The solar ray angle on a particular surface θ_i is expressed as a function of the two solar angles $\theta_{z,i}$ and $\gamma_{s,i}$:

$$\cos \theta_i = \sin \theta_{s,i} \cos{(\gamma_{s,i} - \gamma)} \tag{3.8}$$

3.2 Weather and clearness index

The weather condition greatly affects the amount of direct radiation that reaches the window surface. More in detail, the factor that we have to consider is the clearness of the sky: in a cloudy day, the direct component of solar gains could be dramatically reduced. To do that, the three models account for the clearness index, which is a way to measure the clearness of the atmosphere. It represents the fraction of extraterrestrial solar radiation that reaches the considered surface. In this study we consider the clearness index table developed by Thieblemont et Al. [19]. These values have been designed specifically for the city of Montreal and they represents the clearness index per each weather condition. To build the table, the researchers have collected three type of data: hourly weather conditions forecast, which have been extracted from the weather website of Montreal; historical weather data, that come from an EPW file available on SIMEB website; clear sky model, which have been used to calculate solar radiation.

We set the values of clearness index by following two main reasons. Firstly, we want to simulate a likely scenario for the weather condition in Montreal. Second, we want to challenge the models to work in reasonably hard and interesting conditions. Accordingly, in the winter study case we set the clearness value to be equal to 0.66, which represents a mix of sun and cloud weather. In the summer study case, we set the value to be equal to 1, which represents the worst scenario for cooling. Moreover, we refer to the clearness factor as ϵ: the higher the value, the higher the amount of sun rays reaching the surface.

The amount of solar gains, for each façade, for each time frame is computed as follow:

$$q_{sol,i} = \epsilon(q_{sol,B,i} + q_{sol,D,i}) \quad \forall i \in I \tag{3.9}$$

3.3 Energy cost: time-of-use

The pricing scheme adopted for the models is the Time-of-Use available in Ontario, Canada (see Figure 3.1). The reason to implement just this price-structure is due to its ability to match with the demand response strategy, as showed by Gómez et al. [14]. The models can work for any type of tariff, although it is more interesting to run the cases in which the cost varies during the day. We choose the Ontario tariff since it is already in use. Nevertheless, if also in Quebec the T-o-U is approved, it will be possible to apply it to the three models. It represents fixed electricity prices that Ontario charges to its customers, both residential and small business (electricity demand lower than 50 kW). Time-of-Use (TOU) varies depending on the hours of the day, but also on the season: it defines the effort of the Region to facilitate the balance between supply and demand. It acts as a filter between user and producer, in a way to avoid the user to deal with the energy market. The main purpose is to drive the user's loads away from the on-peak hours.

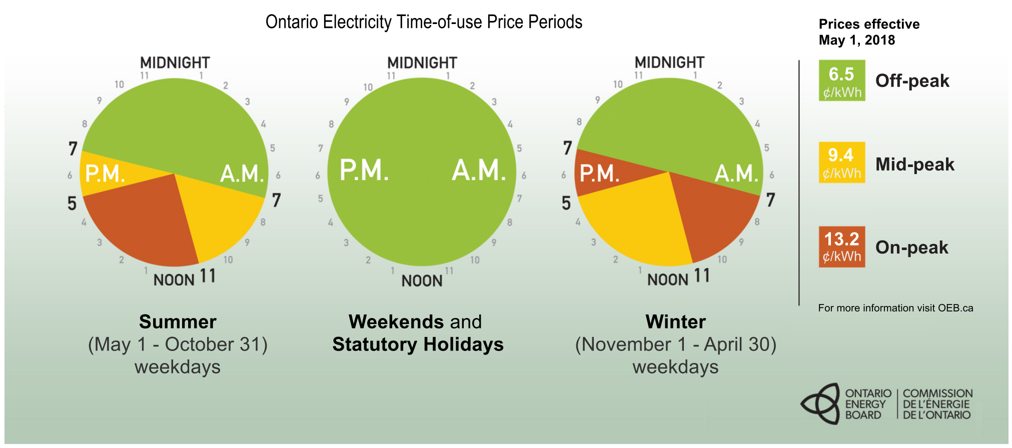

Figure 3.1 Ontario time of use (Ontario Energy Board, 2018)

Three different time windows are presented, each one is linked to an electricity price that encourages the user to consume when energy is cheaper: lower price for off-peak periods, higher price for on-peak and intermediary price for mid-peak. In addition to this, Ontario has also three different schemes according to the season and the type of the day.

CHAPTER 4 STANDARD MODEL

In this chapter we define the model of the standard unit (SM unit), which is the basic unit. The SM unit differs from the PH unit because of the double façade: the basic unit has only one traditional external wall. The units are chategorized according to their orientation and their type of use. In our case, the orientation is the most influential factor, so we start analysing multiple options, collecting them into four study cases: each of them has only one external façade, to better point out the contribution of the orientation (South, North, West and East). We emphasize that all the units have the same geometry (see Figure 4.1) and technical features, the only difference is their orientation: the amount of solar gains and, as consequence, the need for lighting are changing.

The standard model is calibrated using an energy software already in use: SIMEB [6]. This calibration has to be meant as a validation of the three models and it has been done for the two study cases of winter and summer, for all the orientations. Moreover, the input parameters considered to run the models have been calibrated according to the validation with SIMEB. The validation will be presented in the following chapter.

4.1 Physical model

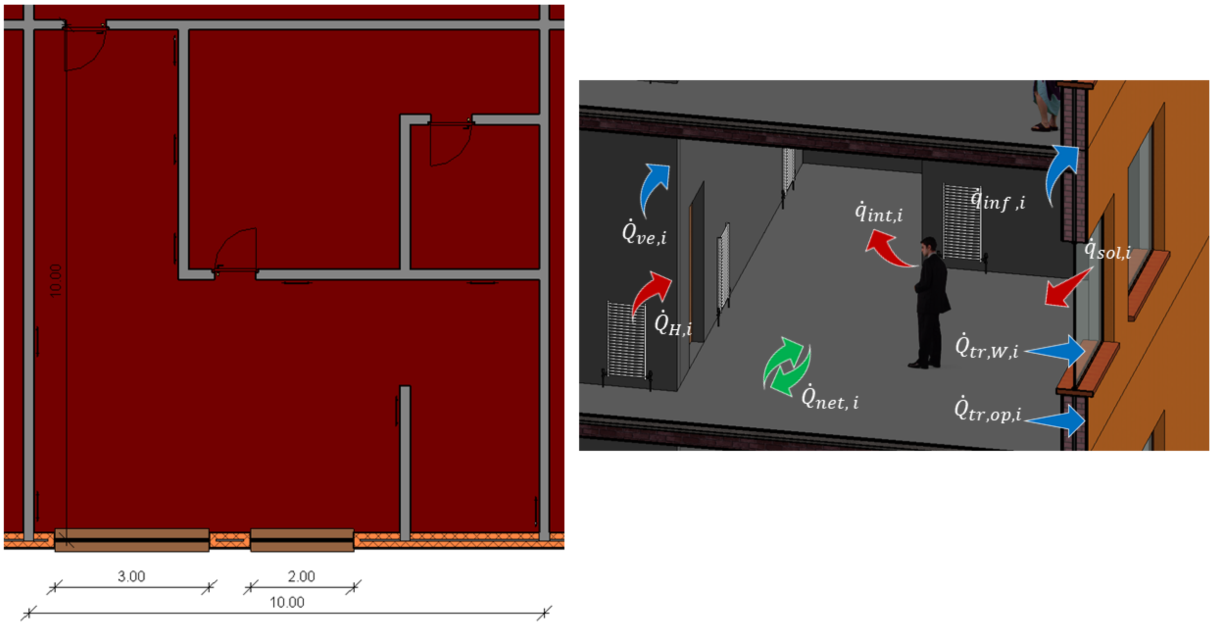

Figure 4.1 The Unit: Energy Balance (Salerno, Ilaria. 2018)

The model is implemented to account for all the energy fluxes that are present in the unit. This model can work with residential, commercial and institutional spaces. By way of example, we design a residential unit: a dwelling.

All the units have the same boundary conditions: there is no thermal flux among neighbouring units and the corridors. In fact, we consider the hypothesis that all the zones have the same temperature inside. Accordingly, concerning the thermal transfer, we account only for the energy exchanges throughout the external wall.

The physical model is characterized by two main types of fluxes: for the winter case, the energy gains are represented in red arrows and the energy losses in blue (Figure 4.1). For the summer case, we still have the same two fluxes, but now, for the mathematical model, the second one is negative: we consider positive, the energy that heats the unit and negative, the energy that the unit is losing (so that makes the unit cooler), for both winter and summer cases.

All the units have the same heating and cooling system, which is centralized at the building level. In detail, we consider heating ventilation and air conditioning device (HVAC) which is in charge to maintain the air quality and to regulate the temperature inside the units. Heat-

ing and cooling are achieved by electric heat pumps and supplied to the units throughout electric baseboards. All the three models consider mechanical ventilation and the humidity level is regulated by the HVAC. Moreover, we assume that the HVAC system has heat recovery ventilation: it recovers the air which has to be extracted from the unit and it uses it for pre-heating the incoming fresh air (the system guarantees 100% fresh air). We consider a cross flow heat recovery ventilation, which has an high efficiency. For our purpose, we set it to be equal to 80% for all the models. Usually, the energy required to pre-heat fresh air is considered at the building level. Nevertheless, we consider it already in the layer 1. Further details about the HVAC system are addressed to the future work related to the layer 2.
The models account for the thermal mass of the walls: for sake of simplicity, we do not consider the thermal mass of furniture nor ceiling and floor. Nevertheless, the models can consider also these elements. We design the same external wall for all the units, which represents a traditional external wall for residential use. It is made up by the following layers: bricks, air, insulation and gypsum.

4.2 Mathematical model

This model, as well as all the other models in this study, is implemented in the programming language of Julia (Julia version 0.6.2 [3]). They are solved via JuMP, by Cbc solver (CbcMathProg). The execution time to run each SM unit is less than 1 second. The model solves 480 linear constraints with 528 variables.
To simulate the SM and the other models in this study, we will consider the equivalent RC circuit. In fact, we represent the thermal behaviour of the unit as an electrical circuit. The SM unit shown in Figure 4.1 is equivalent to the circuit in Figure 4.2. The equivalence between electrical and thermal systems is summarized in Figure 4.4. Accordingly, we design three nodes, each of which is associated to a temperature: the temperature inside the unit (T^{int}), the average temperature of the wall (T^{wall}) and the temperature outside (t^{ext}). We stress out that the elements represented by capital letters are variables for the optimization problem but the others are parameters. We are interested in evaluating the thermal flux which is flowing among the nodes. In the thermal equivalence of a unit, the flux is pushed by the difference between the temperatures of two nodes and it goes from the highest temperature toward the lowest. Walls, windows and the fresh air flowing into the unit, represent a resistance for this flux. Moreover, the wall and the room itself act as a storage: they add inertia to the system and we represent them as capacitors. The higher their thermal mass, the larger is the capacitor impact on the system. There are other thermal fluxes added to the unit-circuit: solar gains (q^{sol}), internal gains (q^{int}) and the ratio coming from the heating

system (Q^H). Moreover, we need to consider the infiltration (q^{inf}) due to the necessity to renew the air inside the unit. The net of all these elements is represented by the value called Q^{in} in Figure 4.2. We want to know from the models which is the optimal temperature to keep inside the unit, per each hour, to minimize the final cost of heating/cooling and lighting, while ensuring comfort.

To better understand the analogy between the unit and the RC circuit, see the example in Figure 4.3. Here we represent the circuit of the south oriented unit, at 12 pm of the second day run. The thermal capacity of the wall is far larger than the one of the room (c_{room} considers the thermal capacity of the air inside the living zone). Accordingly, the wall equivalent capacitor has a greater influence on the entire system. In fact, during this particular time period, almost half of the heat inflow in the living zone is going into the wall-capacitor. Because of that, the temperature of the wall is higher than the one inside the living zone. It is also interesting to notice the different magnitude of the thermal resistance connected to windows and wall. The largest ratio of thermal transfer losses are due to the windows because of their smaller thermal resistance. We will see in the PH model that the additional external skin reduces also thermal transfer thorough windows.

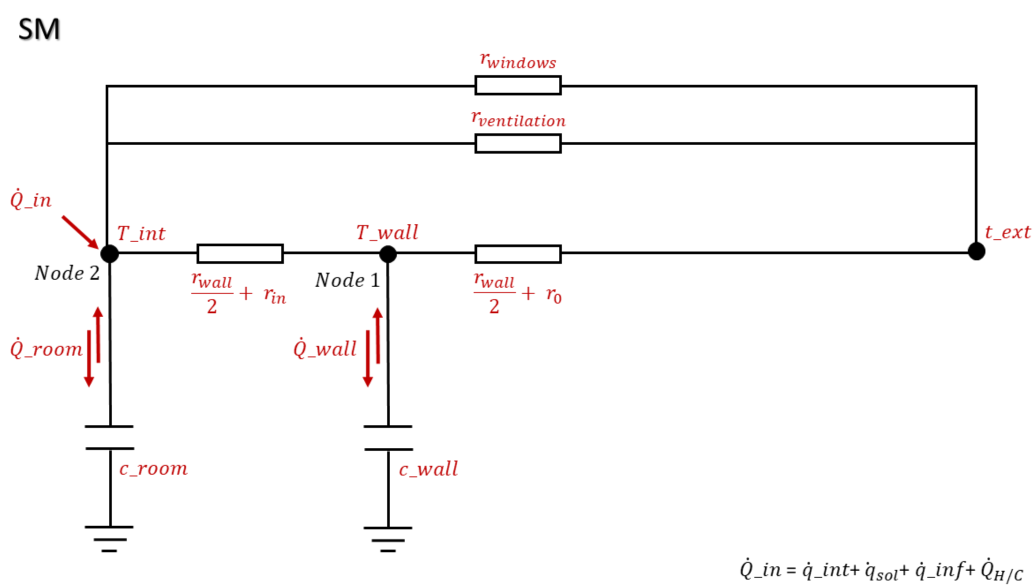

Figure 4.2 SM unit represented by RC circuit (Salerno, Ilaria. 2019)

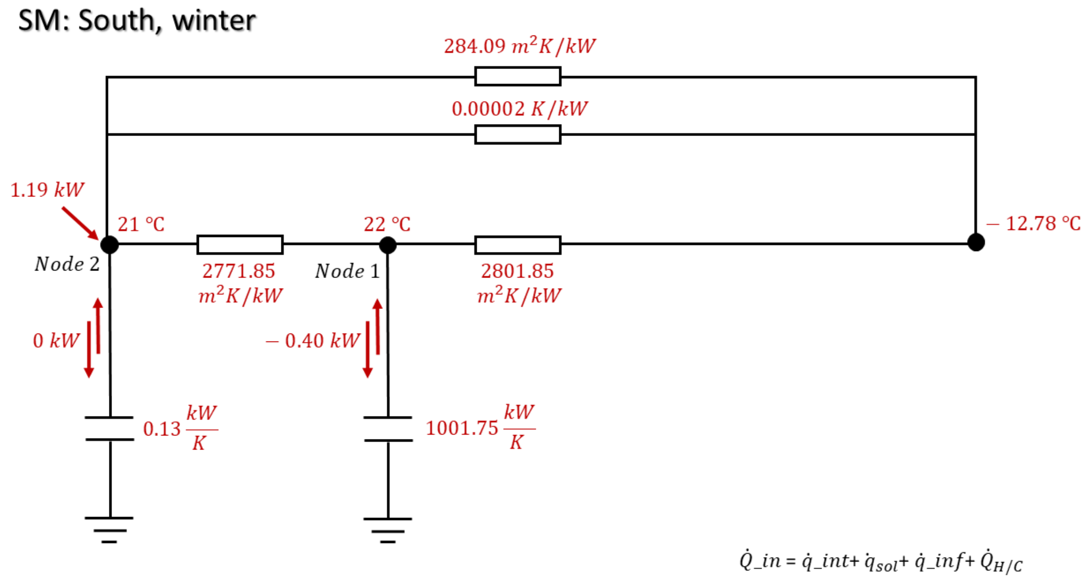

Figure 4.3 SM unit represented by RC circuit. Example of south oriented unit at 12 pm of the second day (Salerno, Ilaria. 2019)

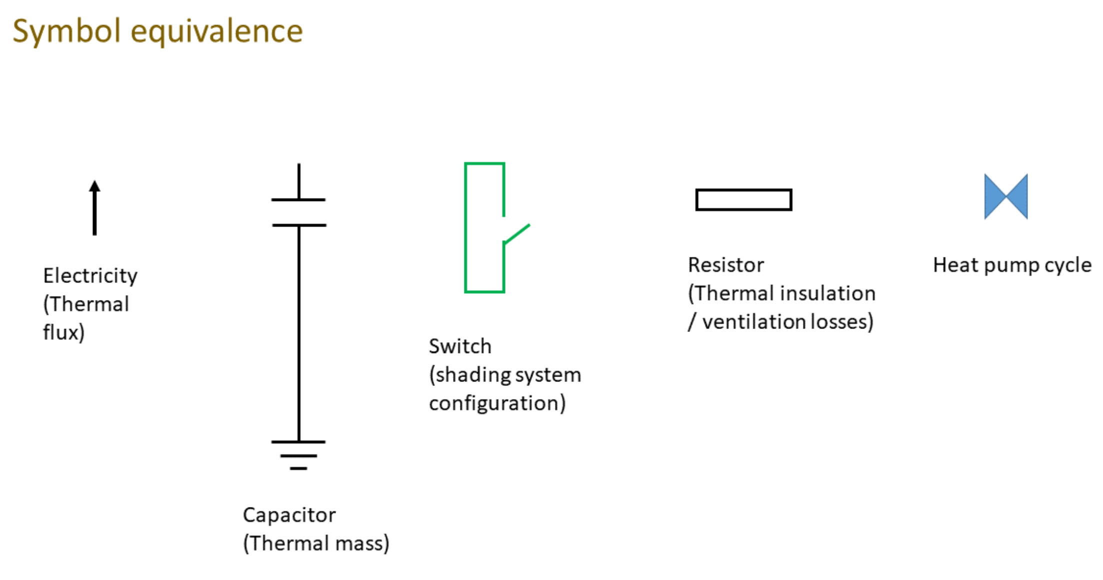

Figure 4.4 Circuit - unit equivalence (Salerno, Ilaria. 2019)

The structure of the mathematical model is shown in the following sections.

4.2.1 Sets

- Time frames: set $I : \{1, ..., m\} \quad \forall i \in I$

4.2.2 Decision variables

- T_i^{int} : Temperature inside the unit [°C], per time period
- Q_i^H : Energy to allocate for the heating system [kWh], per time period
- Q_i^C : Energy to allocate for the cooling system [kWh], per time period

4.2.3 Intermediary variables

- Q_i^{ve} : Energy lost for ventilation [kWh]
- Q_i^{room} : Energy stored inside the unit [kWh] per time period
- Q_i^{wall} : Energy stored in the wall [kWh] per time period
- T_i^{wall} : Average temperature inside the wall [°C] per time period

4.2.4 Parameters

- p_i : Power limit (from the Utility) [kW]
- $q_{B,i}^{sol}$: Energy from solar rays: direct radiation [kWh]
- $q_{D,i}^{sol}$: Energy from solar rays: diffuse radiation [kWh]
- q_i^{sol} : Total energy from solar rays [kWh]
- q_i^{int} : Energy related to people, electronic devices and lighting [kWh]
- q_i^{inf} : Energy related to infiltration [kWh]
- $q_i^{fan,w}$: End-use energy to run ventilation devices during winter [kWh]
- $q_i^{fan,s}$: End-use energy to run ventilation devices during summer [kWh]
- c_i^H : Electricity winter cost [cent/kWh]

- c_i^C : Electricity summer cost [cent/kWh]
- t_i^{ext} External temperature [°C]
- $t_i^{minsetpoint}$: Temperature chosen by the user. It is the lowest temperature that the user will allow [°C]
- $t_i^{maxsetpoint}$: Temperature chosen by the user. It is the highest temperature that the user will allow [°C]
- l^{Up} : Maximum ramping up allowed [°C]
- l^D : Maximum ramping down allowed [°C]
- u_w : Thermal transmittance of windows [kW/m^2 K]
- r_{wall} : Total thermal resistance of the wall [m^2 K/kW]
- r_0 : Thermal resistance between the living zone and the internal surface of the wall [m^2 K/kW]
- $r_{1,2}$: Thermal resistance of the first layer of the wall [m^2 K/kW]
- $r_{2,3}$: Thermal resistance of the second layer of the wall [m^2 K/kW]
- $r_{3,4}$: Thermal resistance of the third layer of the wall [m^2 K/kW]
- $r_{4,5}$: Thermal resistance of the fourth layer of the wall [m^2 K/kW]
- r_{in} : Thermal resistance between the outside and the external surface of the wall [m^2 K/kW]
- a_w : Windows surface [m^2]
- a_{op} : Wall surface [m^2]
- $\dot{m}_{air,i}$: Mass of air that is renewed in the unit per time period [Kg/s]
- $c_{p,air}$: Air specific heat [KJ/Kg K]
- c_{wall} : Wall thermal capacity [KJ/K]
- $\dot{v}_{room}$: Unit volume to heat [m^3/s]
- ρ_{air} : Air density [Kg/m^3]

- ϵ : Clearness index [-]
- β : Efficiency of the heat recovery of the HVAC [-]
- $d_i^{L,w}$: Lighting load in winter [kWh]
- $d_i^{L,s}$: Lighting load in summer [kWh]

4.2.5 Objective function

$$min \quad \sum_{i=1}^{m}((Q_i^H + d_i^{L,w} + q_i^{fan,w})c_i^H + (Q_i^C + d_i^{L,s} + q_i^{fan,s})c_i^C) \tag{4.1}$$

4.2.6 Constraints

Balance, node 1:

$$-\frac{a_{op}}{\frac{r_{wall}}{2} + r_{in}}(T_i^{wall} - T_i^{int}) - Q_i^{wall} - \frac{a_{op}}{\frac{r_{wall}}{2} + r_0}(T_i^{wall} - t_i^{ext}) = 0 \quad \forall i \in I/\{1\} \tag{4.2}$$

Balance, node 2:

$$-a_w u_w(T_i^{int} - t_i^{ext}) + Q_i^H - Q_i^C + q_i^{int} + q_i^{sol} + q_i^{inf} + \tag{4.3}$$

$$+Q_i^{ve} - Q_i^{room} - \frac{a_{op}}{\frac{r_{wall}}{2} + r_{in}}(T_i^{int} - T_i^{wall}) = 0 \quad \forall i \in I/\{1\}$$

Energy required to heat fresh air:

$$Q_i^{ve} = \frac{1-\beta}{100}\dot{m}_{air,i}c_{p,air}(t_i^{ext} - T_i^{int}) \quad \forall i \in I \tag{4.4}$$

Power limit:

$$Q_i^H \leq p_i \quad \forall i \in I \tag{4.5}$$
$$Q_i^C \leq p_i \quad \forall i \in I \tag{4.6}$$

Temperature min limit:

$$T_i^{int} \geq t_i^{minsetpoint} \quad \forall i \in I \tag{4.7}$$

Temperature max limit:

$$T_i^{int} \leq t_i^{maxsetpoint} \quad \forall i \in I \tag{4.8}$$

Ramping Up limit:

$$T_i^{int} - T_{i-1}^{int} \leq l^{Up} \quad \forall i \in I \tag{4.9}$$

Ramping Down limit:

$$T_{i+1}^{int} - T_i^{int} \leq l^{D} \quad \forall i \in I \tag{4.10}$$

Room-capacitor:

$$Q_i^{room} = \dot{v}_{room}\rho_{air}c_{p,air}(T_i^{int} - T_{i-1}^{int}) \quad \forall i \in I \tag{4.11}$$

Wall-capacitor:

$$Q_i^{wall} = c_{wall}(T_i^{wall} - T_{i-1}^{wall}) \quad \forall i \in I \tag{4.12}$$

Non negativity:

$$Q_i^{H} \geq 0 \quad \forall i \in I \tag{4.13}$$

$$Q_i^{C} \geq 0 \quad \forall i \in I \tag{4.14}$$

4.3 Parameters and constraints

In this section, we will explain how parameters and constraints are considered. The calculations are done by following and integrating the two energy Codes that are used to design the air conditioning systems in Europe (European Code: EN ISO 13790: 2008 "Energy Performance of Buildings" [2]) and in Canada (ASHRAE 2009 [1]).
The words *losses* and *gains* are referred to the winter case; in the summer one, the calculation is the same but the losses turn into *heat reentry* and they are negative values.

4.3.1 Losses

Energy required to heat fresh air: Q_i^{ve} and q_i^{inf}
These losses are connected to the ventilation system (HVAC). They are due to the necessity

to pre-heat fresh air flowing into the unit. We assume that the HVAC is centralized at the building level and it has an heat recovery device to pre-heat the external air flux. The efficiency of this heat exchanger is given by the parameter β.

$$Q_i^{ve} = \frac{1-\beta}{100}\dot{m}_{air,i}c_{p,air}(t_i^{ext} - T_i^{int}) \quad \forall i \in I \tag{4.15}$$

where, $\dot{m}_{air,i}$ is the air mass flow of the ventilation system. To evaluate it, we consider the occupancy density of the unit to be equal to $25\frac{m^2}{occupants}$ and the amount of incoming outside air equal to $7.499\frac{l}{s/occupants}$.
In addition to the ventilation losses, the models account also for infiltration losses/gains. These are due to the different pressures and temperatures between the unit and the outside environment. Infiltration losses are important especially for the cooling system. In fact, during summer, infiltration brings not only hot air but also moisture into the unit. We calibrate the infiltration with SIMEB energy software.

Heat transfer losses

The heat transfer losses/gains characterize the thermal flux between the unit and the outside. They are driven by the difference between the inside and outside temperatures and to the technical features of the building envelop. The three models account for heat transfer by conduction, convection and radiation. Convection and radiation are considered in a linearized and simplified way, which is suggested in ASHRAE fundamentals Handbook [1]. In detail, we use the two global heat transfer coefficients related to the inside and outside environments, showed in the table $4-3$ of ASHRAE 2009c. The values of the global heat transfer coefficient are given according to the position of the wall surface, the direction of heat flow and the emittance of the surface.
Looking at Figure 4.2, during winter the heat transfer losses are these fluxes going from the node 2 toward the node connected to the outside temperature (t^{ext}) and passing thorough the wall and windows thermal resistances. During summer, the fluxes are moving in the opposite direction. In fact, the driving force, which is represented by the difference of the node-temperatures, is inverted.
To evaluate the heat transfer, we consider separately the two fluxes through the windows and the wall. Moreover, we account for each material composing the wall. Each layer of the wall is caracterized by a certain material, each of which has its thermal resistance and thermal mass. These two last elements impact the temperature at the interface between one layer and the closest one. We make use of the physical low according which the thermal flux

through the wall has to be equal to the thermal fluxes through each layer of the wall. We do that to better evaluate the temperature inside the unit. In fact, in this way the model can be applied to different wall types. Furthermore, it allows the user to compare different types of wall and the impact that it has on the final electricity cost and consumption.

4.3.2 Gains

Energy gains represent the thermal flux which is warming the unit. They are a parameters from the mathematical point of view. All the gains in SM are considered in the node 2.

Solar gains: q_i^{sol}
They are computed as explained below (see Chapter 3). Solar gains contribute significantly to the energy consumption of the unit. They differentiate one unit from the others and they can represent an advantage or disadvantage. In the SM model, as in the other models presented in this study, we try to benefit from them by considering each unit as a thermal battery.

Internal gains: q_i^{int}
Internal gains represent sensible and latent heat which is emitted by people, electronic devices and lighting system inside the unit. We calibrate these values with SIMEB energy software, accounting for a certain usage profile during the day. In detail, we run the profile PEBC type G (see Figure 7.9), according which there are two main peaks during the working days: the first in the morning and the second in the evening/night. The usage profile impacts not only the values of internal gains but also the lighting electricity demand.

4.3.3 Constraints

There are six sets of constraints:

- Energy flux at the nodes (5.2 and 5.3.4): this constraints are obtained from the Kirchhoff's first current law. Accordingly, flux entering the node must be equal to flux flowing out of it. In other words, we use the charge conservation propriety. In detail, we state that the flux entering the node must be equal to the sum of the fluxes going out of it and stored inside it.
  - Node 1 (Equation 5.2): it represents the thermal flux characterizing the external wall. During winter, the thermal flux is going from the unit (node 2) toward the wall (node 1). In this case, a fraction of the thermal flux flows outside the

unit toward the outdoor environment: these are thermal losses thorough the wall. The other portion is stored inside the wall by the equivalent capacitor. During summer, the flux flows in the opposite direction.

  - Node 2 (Equation 5.3.4): it represents the thermal flux inside the living zone. During winter, the flux connected the net of energy which is warming the unit, is entering the node. A portion of this flux flows toward the external wall (node 1): these are transfer losses thorough the wall. A second ratio is stored inside the unit itself by the equivalent capacitor. A third flux represents the second part of thermal transfer losses: those are losses thorough the windows. The fourth ratio is power lost because of the necessity to change air inside the unit: these are ventilation losses.

- Ventilation losses (Equation 4.4): it is the energy lost to heat the fresh air coming into the unit.

- Power limit (Equation 4.6): it is a technical limit due to the heating/cooling system; more in detail, it depends on the capacity of the heating terminals (for example baseboard) inside the unit.

- Temperatures:

  - Set point into the living zone (Equations 4.7 and 4.8): it represents the user's will and it has a direct influence on the total cost.

  - Ramping limits (Equations 4.9 and 4.10): they limit the speed by which the temperature can change.

- Capacitor (Equations 5.15 and 5.16): these equations represent the inertia of the unit in being heat/cool during a time period.

  - Room-capacitor (Equation 5.15): it represents the flux flowing toward and backward the capacitor. This flux represents the energy stored inside the room. It is connected to the geometry of the unit, to the material composing the storage (which is air, in this case) and to the increasing/decreasing of the temperature inside the unit.

  - Wall-capacitor (Equation 5.16): it represents the flux flowing toward and backward the capacitor. This flux represents the energy stored inside the wall. It is connected to the materials composing the external wall and to the increasing/decreasing of the temperature inside it.

- Non negativity (4.14): we require to have positive values for the variables related to the energy that the unit buys from the electric public grid.

CHAPTER 5 PASSIVE HOUSE

As mentioned before, a *Passive house* is a smart construction that has a very low energy demand. This low consumption is due, mostly, to the clever design project of the building that allows it to have as many benefits as possible from the environment.
In our case, we focus on the capacity of the unit to store thermal energy, both the one bought from the grid and the one obtained from gains. The reason why we may want to store heat is due to the electricity tariff-of-use cost (see Figure 3.1): we want to encourage the user to buy less electricity during the on-peaks, with the aim to save money and to have a lower and more homogeneous consumption.

5.1 Double skin façade

There is a new technology that has a great appeal among building engineers, during these days: it is called *Double skin façade* (DSF) or *Double façade*. Its main advantage is related to the energy-thermal behaviour: it improves ventilation and thermal insulation and, in this sense, the energy savings.
We propose a model of this technology with the aim of using the cavity between the two skins as an heat storage space for the unit. There are two main advantages in doing this: to save money and to keep high quality comfort inside the living zone. As we demonstrate in the following chapters, during its life cycle, the passive house unit is cheaper than the standard model and its energy consumption happens to be far lower than the standard model (SM). It is also possible to keep almost steady the temperature inside its living zone, hence the user is not penalized by the optimization effort of the system.

5.2 Physical model

The Passive house model (PH) has been built on the basis of the standard model (SM) and it represents an improvement of this last model. We run the PH for the four units, one per each orientation, as we did for the SM model. The units considered are mostly the same as those ones that we analysed with the SM model: the only difference consists in the external façade. The PH units have an external skin in addition to the same external wall that we were considering in the SM units. The second skin is made of glass (it is a curtain wall) and the wall has the same features explained for the SM model. The glass external skin, together with the traditional wall and the cavity between them, forms the double skin façade.

There are several typologies of DSF, according to their air cavity. In our case, we design a box window DSF. The cavity modelled, in fact, as to be thought as an individual cell, since each unit has its own space and there is no air flux among different air cavities belonging to different units. The choice of this configuration is connected to architectural reasons. In fact, having large air cavities often means having problems related to the internal pressure. In tall constructions it can happen that the pressure at the top of the building is very different from the one at the basement. This configuration adds complexity for an operation at the unit level. Moreover, the individual cell configuration is safer concerning fire security and it brings higher quality of acoustic comfort. In fact, dividing each cavity from the neighbourhoods, isolates the unit: if a fire starts burning at the basement of the building, it cannot propagates quickly throughout its façade. In the same way, noise propagation among units is reduced.
The key-concept of the Passive house model, is that the living zone benefits from being separated from the outside by the storage space, that is the area in between the two skins of the façade. This space acts as an additional insulation layer and as heat-storage, according to the weather conditions. Moreover, the space inside the cavity in the DSF can be thought as an unconditioned space. The PH model benefits from this environment by the use of an heat pump cycle, both during winter and summer. Finally, the air cavity of the DSF is used by the PH model in three ways: as improved insulation from the outside, as thermal storage and as reservoir to run the heat pump cycle (or the reverse cycle, during summer).
The heat pump cycle will work between two reservoirs. During winter, the cold one is the storage and the hot one is represented by the living zone. We want to move the heat from the cold sink to the hot one: this is the opposite direction of the spontaneous heat transfer, so we need to do work. The work is done by the compressor that acts on a refrigerator. The refrigerator evaporates in the storage, taking thermal energy from this space; after that, it is pushed into the compressor where its pressure in increased and it moves into the living zone, where it condensates, by releasing the heat. The electricity required by the compressor will be considered into the objective function of the PH model, as well for the boiling point of the refrigerator. Nevertheless, the PH model will arise to be significantly cheaper than a standard optimized house (SM).
We will show that the PH model has better energy performances not only during winter, but also during summer, where the heat pump cycle works as reverse cycle. During summer, the compressor works to cool the living zone by using the storage has heat sink.
The model obtains the temperatures inside the storage and the living zone, by considering the amount of energy inside the area and the temperature connected to it per each time period. By doing that, we are accounting for the local greenhouse effect too. Even inside the storage cavity, the PH model is considering the three types of thermal heat transfer:

conduction, convection and radiation. The cavity is $0.80m$ depth, which means that the convective component is relevant. Because of that, we consider the global heat transfer coefficients suggested by ASHRAE [1] to calculate the temperature inside the storage.

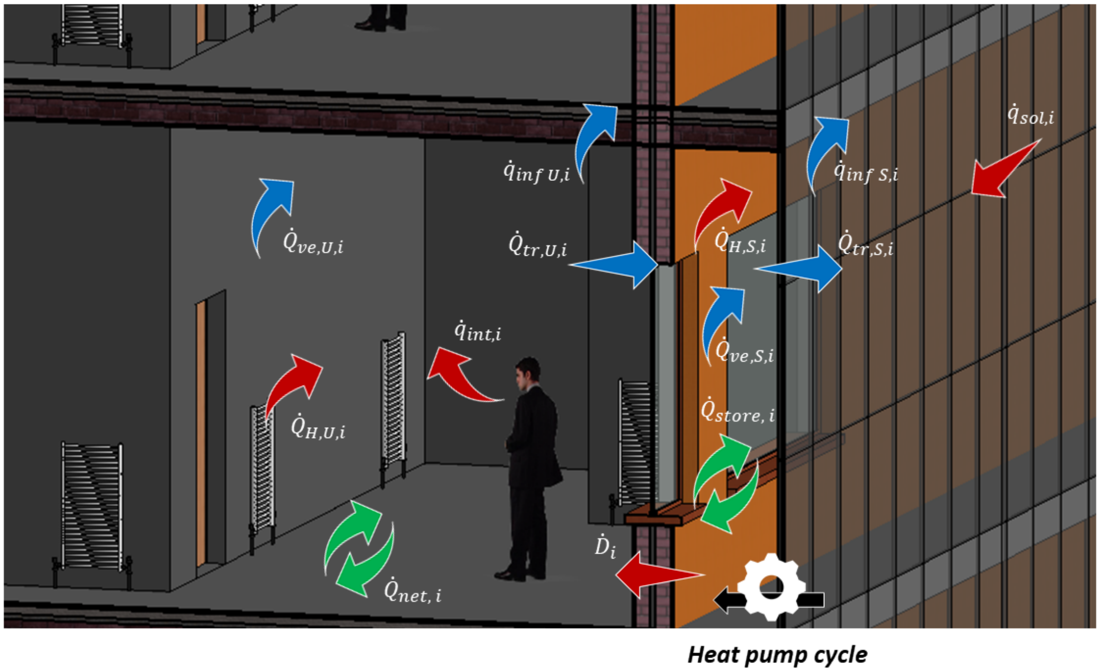

Figure 5.1 Double skin technology: Energy Balance (Salerno, Ilaria. 2018)

The temperature inside the storage and the living zone are bound to stay inside a set point range. During summer, the space inside the façade acts as a filter between the living zone and the outside. In fact, it captures the solar rays before that they can reach the unit. Because of that, the PH units are characterised by high quality visual and thermal comfort. In addition to that, by changing the input values of some parameters in the model, it is possible to simulate an opening between the storage and the outside or between the living zone and the storage. In fact, opening one of these two overtures means increasing the ventilation losses, which are connected to the parameters $\dot{m}^S_{air,i}$ and $\dot{m}^U_{air,i}$.

The PH model does not account for louvres. Traditional blinds can eventually be added to the system by accounting for their influence on solar gains. Nevertheless, it is more interesting to analyse more developed typologies, such as automated shadings. The dynamic model (DYN) presented in the next chapter explores this idea. In fact, the DSF represents an advantage concerning the louvres: setting the shading system in the air cavity allows to better preserve it. Because of that, it is interesting to model a more sophisticated system which otherwise is too delicate to be kept outside the façade.

5.3 Mathematical model

This model, as well as all the other models in this study, is implemented in the programming language of Julia (Julia version 0.6.2 (3)). It is solved via JuMP, using the Cbc solver (CbcMathProg). The execution time to run each PH unit is less than 1 second. The model has 816 linear constraints with 864 variables.

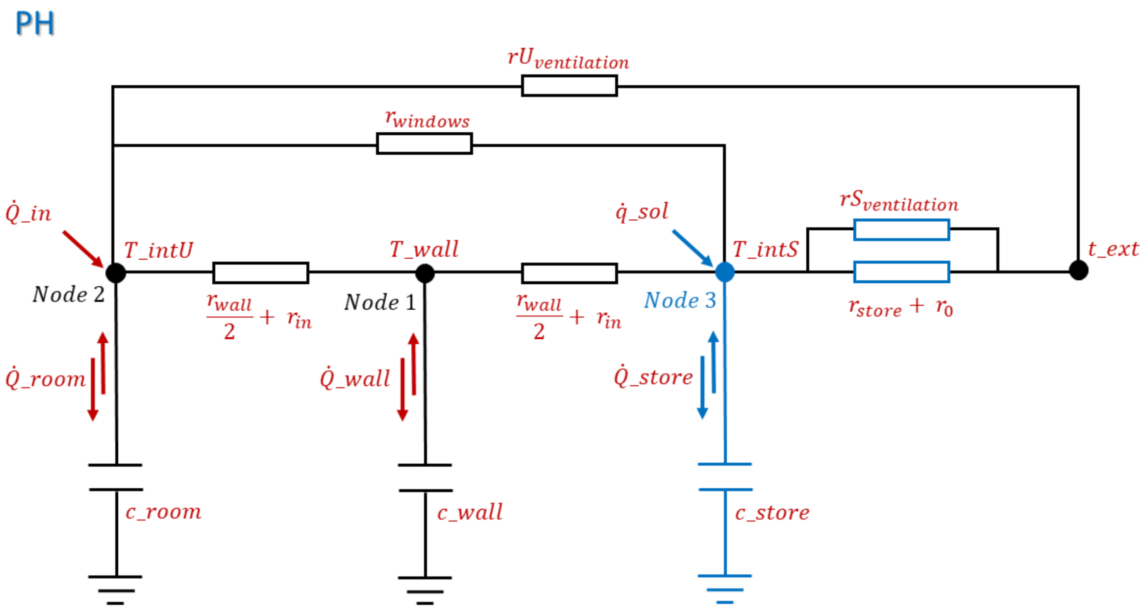

Figure 5.2 PH unit without heat pump, represented by RC circuit (Salerno, Ilaria. 2019)

As we did for the SM model, we represent the PH model by the equivalent RC circuit. The main difference between the two circuits is the node 3: we consider an additional node to the circuit, which is connected to the temperature of the storage-cavity (see Figures 5.2 and 5.3). As for the other two nodes, the node 3 is connected to a capacitor which represents the thermal inertia of the double façade. In this study, the thermal inertia of the double façade consists in the thermal mass of the air inside its cavity. Moreover, it is necessary to ventilate the cavity, so we add thermal losses due to natural ventilation also between the node 3 and the outside. The second important difference from the SM model, is represented by the inflow of the nodes 3: the PH model captures more solar gains than the SM and their displacement in the unit is different. The third and last difference is a consequence of the first two: transfer losses through windows are connected to the temperature inside the storage (node 3) and not anymore to the temperature outside. Figure 5.3 represents the heat pump

added to the circuit. It connects the nodes 2 and 3. During winter the heat pump works between the cold reservoir (node 3) and the hot one (node 2). During summer, the cycle is reversed.
As we did for the SM equivalent circuit, we represent in Figure 5.4 the behaviour of the south oriented unit during the second day at 12 pm. In this study, the thermal mass of both storage-cavity and room is characterized only by air. Because of that, they are far smaller than the thermal mass of the wall. Nevertheless, the power flux flowing into the storage-capacitor is smaller than the one flowing into the room-capacitor. This happens because the temperature of the storage varies more than the one of the living zone. It is interesting to notice that the heat pump is pushing almost the entire amount of solar gains toward the living zone. By doing that, the unit does not need to buy electricity to run the heat system: it only needs electricity to run the heat pump cycle, which is less expensive.

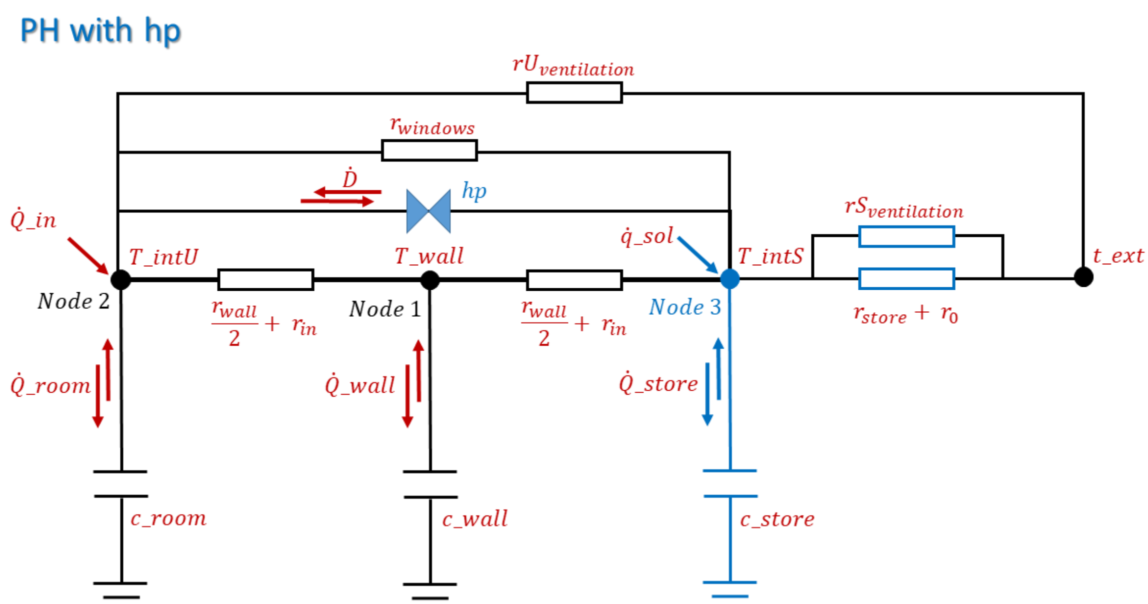

Figure 5.3 PH unit with heat pump, represented by RC circuit (Salerno, Ilaria. 2019)

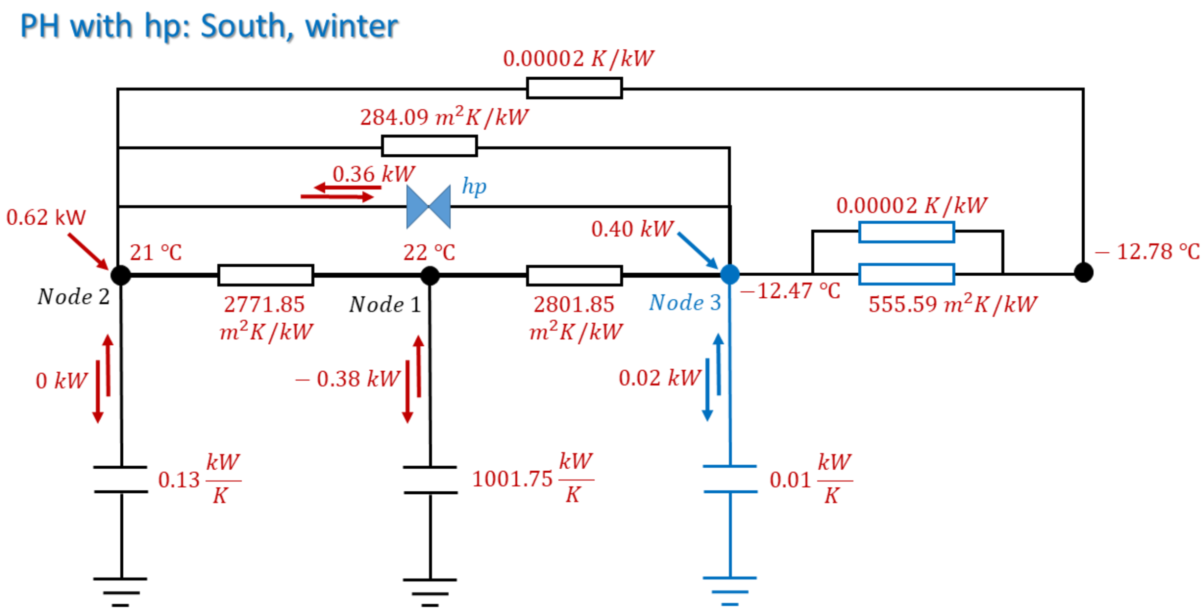

Figure 5.4 PH unit with heat pump, represented by RC circuit. Example of south oriented unit at 12 pm of the second day (Salerno, Ilaria. 2019)

5.3.1 Decision variables

- $Q^H_{U,i}$: Energy to allocate inside the living zone for the heating system [kWh], per time period
- $Q^H_{S,i}$: Energy to allocate inside the storage for the heating system [kWh], per time period
- $Q^C_{U,i}$: Energy to allocate inside the living zone for the cooling system [kWh], per time period
- $Q^C_{S,i}$: Energy to allocate inside the storage for the cooling system [kWh], per time period
- $T^{int}_{U,i}$: Temperature inside the living zone [°C], per time period
- $T^{int}_{S,i}$: Temperature inside the storage [°C], per time period
- W^H_i : Energy to allocate for the compressor of the heat pump cycle [kWh] during winter, per time period

- W_i^C : Energy to allocate for the compressor of the heat pump cycle [kWh] during winter, per time period

5.3.2 Intermediary variables

$Q_{U,i}^{ve}$: Energy lost to heat fresh air flowing in the living zone [kWh] $Q_{S,i}^{ve}$: Energy lost to heat fresh air flowing in the storage [kWh] Q_i^{room} : Energy stored inside the living zone, as heat, per time period [kWh] Q_i^{store} : Energy stored inside the double façade, per time period [kWh] Q_i^{wall} : Energy stored in the wall per time period [kWh] T_i^{wall} : Average temperature inside the wall [°C] per time period D_i : Energy discharged from the heat-storage [kWh], per time period

5.3.3 Parameters

- p_i : Power limit (from the Utility) [kW]
- $q_{B,i}^{sol}$: Energy from solar rays: direct radiation [kWh]
- $q_{D,i}^{sol}$: Energy from solar rays: diffuse radiation [kWh]
- $q_{U,i}^{sol}$: Total energy from solar rays captured by the internal skin [kWh]
- $q_{S,i}^{sol}$: Total energy from solar rays captured by the external skin [kWh]
- q_i^{int} : Energy related to people, electronic devices and lighting [kWh]
- q_i^{inf} : Energy related to infiltration [kWh]
- $q_i^{fan,w}$: End-use energy to run ventilation devices during winter [kWh]
- $q_i^{fan,s}$: End-use energy to run ventilation devices during summer [kWh]
- c_i^H : Electricity winter cost [cent/kWh]
- c_i^C : Electricity summer cost [cent/kWh]
- t_i^{ext} External temperature [°C]
- $t_{U,i}^{maxsetpoint}$: Temperature chosen by the user. It is the highest temperature that the user will allow inside the living zone [°C]
- $t_{U,i}^{minsetpoint}$: Temperature chosen by the user. It is the lowest temperature that the user will allow inside the living zone [°C]

- $t_{S,i}^{maxsetpoint}$: It is the highest temperature that the the technology chosen can support, inside the storage [°C]
- $t_{S,i}^{minsetpoint}$: It is the lowest temperature that the the technology chosen can support, inside the storage [°C]
- l_U^{Up} : Maximum ramping up allowed for the living zone [°C]
- l_U^D : Maximum ramping down allowed for the living zone [°C]
- l_S^{Up} : Maximum ramping up allowed for the storage [°C]
- l_S^D : Maximum ramping down allowed for the storage [°C]
- $u_{U,w}$: Thermal transmittance of the windows in the living zone (internal skin) [kW/m^2 K]
- u_S : Thermal transmittance of the storage (external skin) [kW/m^2 K]
- r_{wall} : Total thermal resistance of the wall [m^2 K/kW]
- r_0 : Thermal resistance between the living zone and the internal surface of the wall [m^2 K/kW]
- $r_{1,2}$: Thermal resistance of the first layer of the wall [m^2 K/kW]
- $r_{2,3}$: Thermal resistance of the second layer of the wall [m^2 K/kW]
- $r_{3,4}$: Thermal resistance of the third layer of the wall [m^2 K/kW]
- $r_{4,5}$: Thermal resistance of the fourth layer of the wall [m^2 K/kW]
- r_{in} : Thermal resistance between the outside and the external surface of the wall [m^2 K/kW]
- a_w : Window's surface (internal skin) [m^2]
- a_{op} : Wall's surface (internal skin) [m^2]
- a_S : Curtain wall's surface (external skin) [m^2]
- $\dot{m}_{air,i}^U$: Mass of air that is renewed in the living zone per time period [Kg/s]
- $\dot{m}_{air,i}^S$: Mass of air that is renewed in the storage per time period [Kg/s]
- $c_{p,air}$: Air specific heat [KJ/Kg K]

- c_{wall} : Wall thermal capacity [KJ/K]
- $\dot{v}_{room}^{U}$: Air volume in the living zone $[m^3/s]$
- $\dot{v}_{room}^{S}$: Air volume in the storage $[m^3/s]$
- ρ_{air} : Air density $[Kg/m^3]$
- ϵ : Clearness index [-]
- β : Efficiency of the heat recovery of the HVAC [-]
- $d_i^{L,w}$: Lighting load in winter [kWh]
- $d_i^{L,s}$: Lighting load in summer [kWh]
- e^H : Efficiency of the heat pump cycle for heating [-]
- e^C : Efficiency of the heat pump cycle for cooling [-]

5.3.4 Objective function

$$min \quad \sum_{i=1}^{m}((Q_{U,i}^{H} + Q_{S,i}^{H} + d_L^w + W_i^H + q_i^{fan,w})c_i^H + (Q_{U,i}^{C} + Q_{S,i}^{C} + d_L^s + W_i^C + q_i^{fan,w})c_i^C)) \quad \forall i \in I/\{1\} \tag{5.1}$$

Constraints

Balance, node 1:

$$-\frac{a_{op}}{\frac{r_{wall}}{2} + r_{in}}(T_i^{wall} - T_{U,i}^{int}) - Q_i^{wall} - \frac{a_{op}}{\frac{r_{wall}}{2} + r_{in}}(T_i^{wall} - T_{S,i}^{int}) = 0 \quad \forall i \in I/\{1\} \tag{5.2}$$

Balance, node 2:

$$-a_w u_w(T_{U,i}^{int} - T_{S,i}^{int}) + Q_{U,i}^{H} - Q_{U,i}^{C} + q_i^{int} + q_i^{sol} + q_i^{inf} + \tag{5.3}$$

$$+Q_{U,i}^{ve} - Q_i^{room} - \frac{a_{op}}{\frac{r_{wall}}{2} + r_{in}}(T_{U,i}^{int} - T_i^{wall}) + D_i = 0 \quad \forall i \in I/\{1\}$$

Balance, node 3:

$$-Q_i^{store} - \frac{a_{op}}{\frac{r_{wall}}{2} + r_{in}}(T_{S,i}^{int} - T_i^{wall}) + Q_{S,i}^{H} - Q_{S,i}^{C} + q_{S,i}^{sol} + \tag{5.4}$$

$$+Q_{S,i}^{ve} - a_S(u_S + \frac{1}{r_0})(T_{S,i}^{int} - t_i^{ext}) - D_i = 0 \quad \forall i \in I/\{1\}$$

Pre-heat load, storage:

$$Q_{S,i}^{ve} = \frac{1-\beta}{100}\dot{m}_{air,i}^{S} c_{p,air}(T_{S,i}^{int} - t_i^{ext}) \quad \forall i \in I \tag{5.5}$$

Pre-heat load, living zone:

$$Q_{U,i}^{ve} = \frac{1-\beta}{100}\dot{m}_{air,i}^{U} c_{p,air}(T_{U,i}^{int} - t_i^{ext}) \quad \forall i \in I \tag{5.6}$$

Temperature min, storage:

$$T_{S,i}^{int} \geq t_{S,i}^{minsetpoint} \quad \forall i \in I \tag{5.7}$$

Temperature max, storage:

$$T_{S,i}^{int} \leq t_{S,i}^{maxsetpoint} \quad \forall i \in I \tag{5.8}$$

Temperature min, living zone:

$$T_{U,i}^{int} \geq t_{U,i}^{minsetpoint} \quad \forall i \in I \tag{5.9}$$

Temperature max, living zone:

$$T_{U,i}^{int} \leq t_{U,i}^{maxsetpoint} \quad \forall i \in I \tag{5.10}$$

Ramping Up limit, storage:

$$T_{S,i}^{int} - T_{S,i-1}^{int} \leq l_S^{Up} \quad \forall i \in I \tag{5.11}$$

Ramping Down limit, storage:

$$T^{int}_{S,i+1} - T^{int}_{S,i} \leq l^{D}_{S} \quad \forall i \in I \tag{5.12}$$

Ramping Up limit, living zone:

$$T^{int}_{U,i} - T^{int}_{U,i-1} \leq l^{Up}_{U} \quad \forall i \in I \tag{5.13}$$

Ramping Down limit, living zone:

$$T^{int}_{U,i+1} - T^{int}_{U,i} \leq l^{D}_{U} \quad \forall i \in I \tag{5.14}$$

Room-capacitor:

$$Q^{room}_{i} = \dot{v}_{room}\rho_{air}c_{p,air}(T^{int}_{U,i} - T^{int}_{U,i-1}) \quad \forall i \in I \tag{5.15}$$

Wall-capacitor:

$$Q^{wall}_{i} = c_{wall}(T^{wall}_{i} - T^{wall}_{i-1}) \quad \forall i \in I \tag{5.16}$$

Storage-capacitor:

$$Q^{store}_{i} = \dot{v}^{S}_{room}\rho_{air}c_{p,air}(T^{int}_{S,i} - T^{int}_{S,i-1}) \quad \forall i \in I \tag{5.17}$$

Compressor

$$W^{H}_{i} = \frac{D_i}{e^H} \quad \forall i \in I \tag{5.18}$$

$$W^{C}_{i} = \frac{D_i}{e^C} \quad \forall i \in I \tag{5.19}$$

Non negativity

$$Q_{S,i}^{H} \geq 0 \quad \forall i \in I \tag{5.20}$$
$$Q_{U,i}^{H} \geq 0 \quad \forall i \in I \tag{5.21}$$
$$Q_{S,i}^{C} \geq 0 \quad \forall i \in I \tag{5.22}$$
$$Q_{U,i}^{C} \geq 0 \quad \forall i \in I \tag{5.23}$$
$$W_{i}^{H} \geq 0 \quad \forall i \in I \tag{5.24}$$
$$W_{i}^{C} \geq 0 \quad \forall i \in I \tag{5.25}$$

5.4 Parameters and constraints

5.4.1 Parameters

In the PH study case, it is necessary to add all the parameters related to the space that we have called “storage” . As in the SM model, in the PH we keep the hypothesis of adiabatic condition among neighbouring units. The air cavity which constitutes the storage, defines a delimited space: each unit has its own storage and, at this level, there is no energy exchanges among the units. Nevertheless, the interaction among the storages belonging to different units is an interesting topic for the future development of the Multilayer system. For the SM model we have only one value related to the temperature inside the unit (T_i^{int}), for the PH one, we have two different parameters, one related to the living space and the other to the storage area ($T_{U,i}^{int}$ and $T_{S,i}^{int}$). The energy to allocate ($Q_{U,i}^{H}$, $Q_{S,i}^{H}$, $Q_{U,i}^{C}$ and $Q_{S,i}^{C}$) and the energy lost for ventilation ($Q_{U,i}^{ve}$ and $Q_{S,i}^{ve}$). The parameters related to the temperature set point, the ramping constraints, the thermal transmittance, the surface area and the air of mass and volume of the zone, are designed in the same way. In addition to that, there are three main differences in the mathematical models of SM and PH. Firstly, the PH has to account for the electricity required to run the compressor of the heat pump cycle. To do that, we enter the variable W_i: it represents the energy to allocate for the compressor and it is included into the objective function for both winter and summer. By doing that, the model accounts for the expense needed to run the heat pump cycle. Secondly, we model the space between the two skins, as a battery. This thermal storage can exchange heat with the living space and to do that, it uses the variable D_i. This variable represents the amount of energy that passes from the storage space to the living zone, per each time period. To conclude, we include another variable: the net of energy inside the storage space (Q_i^{store}), that can be thought as the equivalent of Q_i^{room} for the living zone. If we think about the thermal storage as a battery, we can see the variable D_i as the discharging and the variable Q_i^{store} as the state

of the capacity of the battery.
The variables Q_i^{store} and Q_i^{room} are particularly interesting because they represent the amount of energy that the unit is able to store during each time period i. They are directly linked to the internal temperatures ($T_{S,i}^{int}$ and $T_{S,i}^{int}$), which are the decision variables of the mathematical model: the final purpose is to know which is the internal temperature per each time period, to achieve the minimum final cost. Moreover, by increasing the physical space where the energy can be stored, we make the storage potential of the PH model be larger than the one of the SM. In addition to that, the storage space is allowed to reach higher temperatures because they do not affect the comfort in the unit.

5.4.2 Constraints

The PH model has the same six sets of constraints as the SM model, plus a new one related to the heat pump. In fact, we have to enter two additional constraints to account the working-temperatures of the refrigerant and the energy to allocate for the compressor of the heat pump cycle. Moreover, the external skin impacts significantly the transfer losses. We model the losses through the external skin as we did for the the wall in the SM model. We highlight that the model is still accounting for conduction, convection and radiation. We do that by considering the global heat transfer coefficients also inside the storage cavity.
In detail, the new constraints added are: the balance at the node 3 (Equation 5.3.4), ventilation losses related to the storage-cavity (Equation 5.5), temperature set point and ramping (Equations 5.7, 5.8, 5.3.4 and 5.3.4), storage-capacitor (Equation 5.17), the heat pump cycle (Equations 5.18 and 5.19) and the non negativity constraints connected to the new variables. Among them, it is interesting to point out the following constraints: the balance at the node 3, the minimum temperature set point of the storage and the compressor constraint. The other new constraints have been designed following the SM model.

- Node 3 (5.3.4) :

  As we did for the other two nodes, in this constraint we use Kirchhoff's current law. At the node 3 the inflow represented by the sum of solar gains and the thermal transfer coming from the unit thorough wall and windows, has to be balanced by the outflow toward the outside, the flux which represents the energy stored inside the double façade and the ratio used by the heat pump cycle.

- Heat-storage: the refrigerant (5.7, 5.8)

  To move the heat stored inside the façade, toward the living zone, we model a system that uses the refrigerant $R410a$, which is common for small heat pumps. For our mathematical model, it means to take the temperature of the storage cavity ($T_{S,i}^{int}$), inside the operating temperature range of the refrigerant. There is an important point to stress out while deciding the temperature range set point: the efficiency of the heat pump depends on its working temperature. Because of that, we first set the seasonal efficiency of the heat pump (SCOP) and after we build the set point constraints (5.7, 5.8) to force the temperature to stay inside the range. By doing this, we ensure that the heat pump is always working inside the temperature range which can guarantee the SCOP set. To decide those values, we refer to technical sheets of heat pump in the market. We account for two different air heat pumps, one for winter and the other for summer. Nevertheless, it is possible to use a reverse heat pump, which can work in both the heating and cooling mode. The model considered in the winter study case is Ecodan PUHZ Monobloc, which guarantees the SCOP of 4.06 when it works inside the operating temperatures of $-25/+35°C$. During summer we consider the Hitachi Shirokuma, which can guarantee the SCOP of 4.50 if working inside the range of $-10/+43°C$.

- Compressor of the heat pump cycle (5.18, 5.19):
  This constraint designs the amount of electricity which the unit has to buy from the power grid to run the heat pump. This value is represented by the variables W_i^H and W_i^C, respectively for heating and cooling. The electricity to be bought, depends on both the amount of energy discharged by the storage-cavity (D_i) and the efficiency of the heat pump (e). According to the operating temperature range defined by the constraints 5.7 and 5.8, we set e to be equal to the two SCOP discussed above.

CHAPTER 6 DYNAMIC FACADE: SOLAR GAINS

When we will analyse the behaviour of all the orientations, we will see that some units are more advantageous than others because of their orientation.
Taking this in consideration, we propose the dynamic façade technology as a solution for three main issues. Firstly, to reduce the demand peak of electricity before the on-peak hours. Secondly, to make the living quality conditions uniform throughout the units. Third, to reduce even more the energy cost and improving the internal comfort, by limiting the fluctuation of the temperature inside the living zone.
Accordingly, this technology brings benefits to both user and Utility side. The final cost includes the electricity required to move the shading system, even if it can vary significantly from a type to another.

6.1 Dynamic façade technology

The energetic behaviour of a building depends on its façades, indeed they act as filters between the living space and the exterior.
Because of the dynamism of the environment, it is clear that, if this filter is able to adapt to the exterior dynamic inputs, the entire optimization system will benefit. In the literature, it has already been shown by Hammada and Abu-Hijleh [24] that a dynamic façade technology can save between 24.4% and 34.02% of energy consumed. We want to demonstrate in this chapter that the dynamic façade can be implemented into a larger and more general optimization model, with the aim to merge the façade's dynamism and the storage behaviour, to better manage the electricity market structure.
The idea behind the dynamic façade is simple: the unit no longer has fixed external walls but its façade is able to stop, partially or totally, the solar rays incident on them. This solar control can be done by old-fashion wood sunshades (see Figure 6.2), by standard and cheaper blinds, by more complex shading systems (see Figure 6.1) and by the so called "Adaptive solar façade" . They can move by using different input types, from the electricity one to the natural thermal expansion due to the solar rays.

Figure 6.1 Dynamic façade, Al Bahar Headquarter, Abu-Dhabi, United Arab Emirates (Inhabitat, 2014)

Figure 6.2 Dynamic façade, Surry Hills, Sydney, Australia (Elekhh, 2010)

6.2 Dynamic façade into our model

The dynamic model starts from the PH one. In fact, we take the PH model and we add the automated shading system (see Figure 6.3), linked to the constrains explained below.

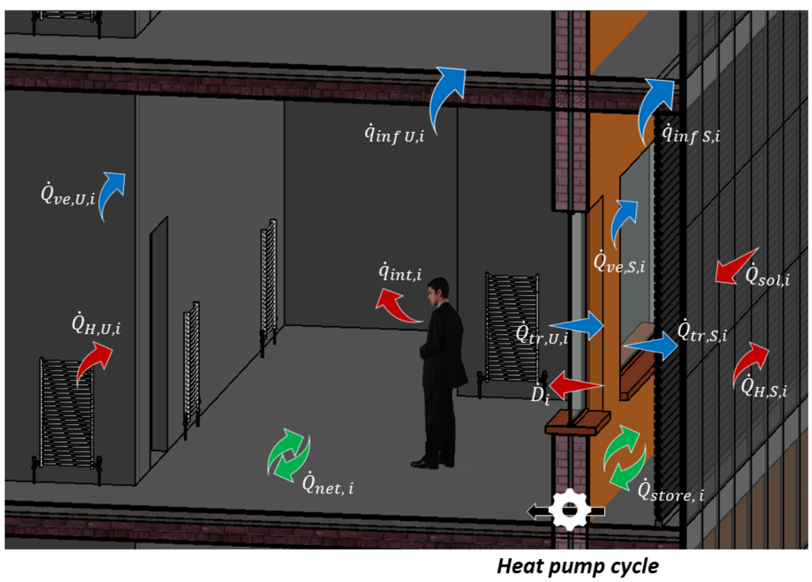

Figure 6.3 Dynamic façade technology (Salerno, Ilaria. 2018)

The Dynamic model (DYN) simulates an active solar shading, which is controlled by the optimization model. The shadings system operated by a motor, whose electricity requirements are included into the objective function. The innovative aspect of DYN is connected to solar gains. The most significant change passing from the PH model to the DYN is related to the fact that, until now solar gains were parameters for the optimization problem; at this moment, they become variables. When the amount of solar gains happens to be too expensive for the cooling system of the unit, the DYN model can reduce it by closing the solar shading system. The DYN model happens to brings significant advantages during summer, while during winter it runs the same results of the PH model. In fact, solar gains help to warm the unit during winter, so the optimal solution is to keep the shadings opened with the aim of capturing the highest amount of energy from the sun.

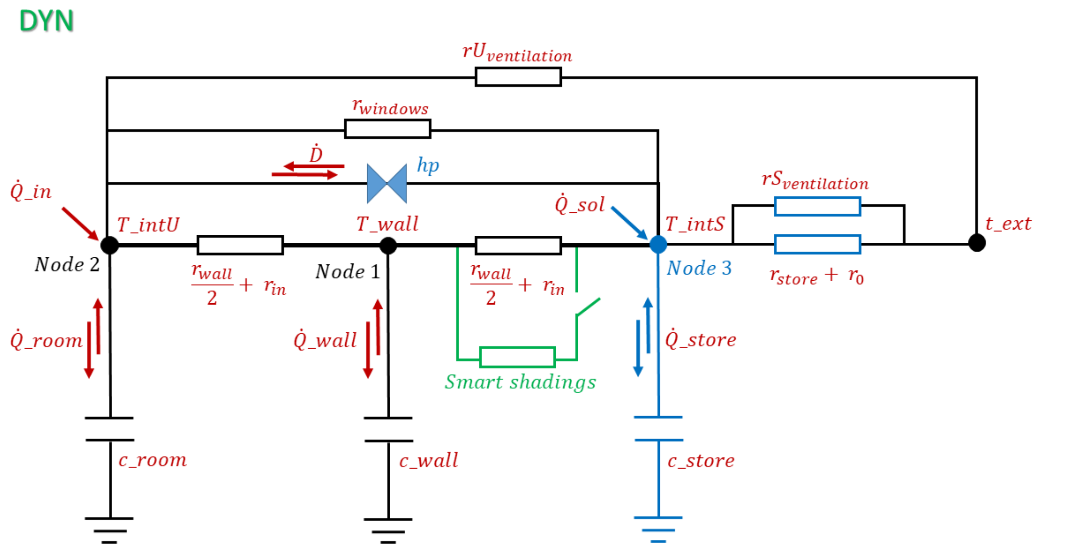

Figure 6.4 Dynamic façade technology, represented by RC circuit (Salerno, Ilaria. 2019)

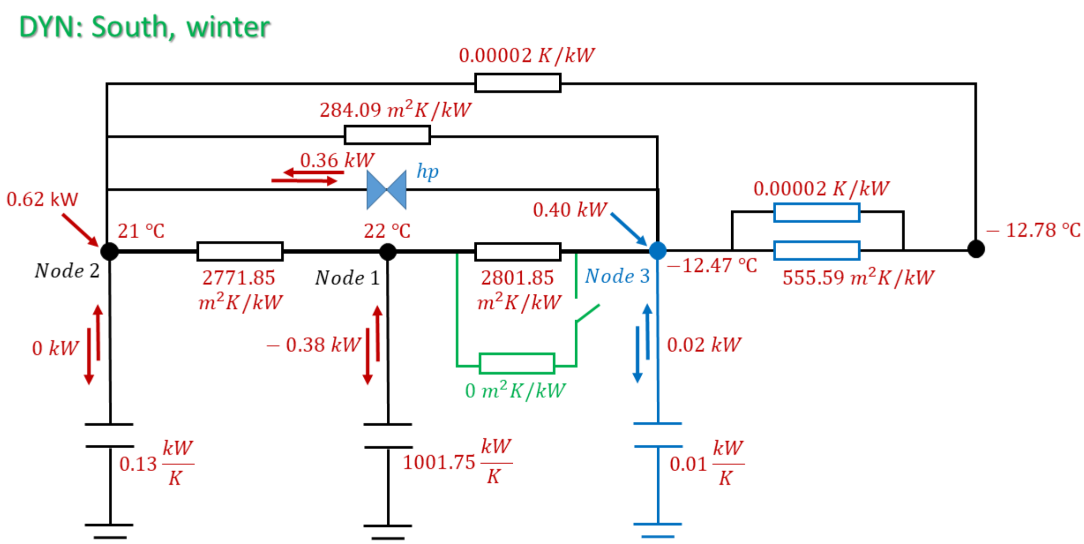

Figure 6.5 Dynamic façade technology, represented by RC circuit. Example of south oriented unit at 12 pm of the second day (Salerno, Ilaria. 2019)

Looking at the equivalent RC circuit (Figure 6.4), the shading system can be thought as an increase of the external thermal resistance. Moreover, we can control the amount and timing of this increasing of resistance because of the optimization problem.
In Figure 6.5 we represent the south oriented unit at 12 pm of the second day as example. As we will see later, during winter the optimal solution is to have as much solar gains as possible entering the living zone. Because of that, the DYN model decides to keep the shadings opened: it is not using the additional thermal resistance and the DYN model acts as the PH model. On the other side, during summer it is more convenient to close the shadings (i.e to increase the thermal resistance between outside and living zone). We will study it in more detail in the next chapters.
This model, as well as all the other models in this study, is implemented in the programming language Julia (Julia version 0.6.2 (3)). It is solved via JuMP, using the Cbc solver (CbcMathProg). The execution time to run each DYN unit is less tha 1 second. The model solves 1008 linear constraints with 960 variables, where 48 of which are binary variables.
The DYN model is a Mixed integer linear problem, which includes one binary variable. This binary variable represents the configuration of the shadings and it allows the model to account for the cost required to move it.
To design the DYN model, we enter the following variables:

- Δ_i : Shading coefficient [-]
- x_i : Binary variable [-]

And the parameter:

- λ : Lighting penalty [kWh]

The variable Δ_i controls the configuration of the solar shadings per each time period. It can vary inside a certain range, which is chosen by the user. In fact, the user may allow the shadings to totally close or decide to always have a certain amount of natural light inside the unit. We choose the second option in our experiments: we always want to ensure a certain amount of natural daylight inside the living zone. Accordingly, we allow Δ to vary from 0.3 to 1, where $\Delta_i = 1$ means that the shadings are totally opened. The value of 0.3 comes from considerations about visual comfort. In fact, to guarantee proper visual comfort, we consider the illuminance threshold. We refer to the Literature, especially to the work of Acosta et Al. [25] where the illuminance threshold of 250 lux is considered sufficient to develop all the tasks inside a common residential unit. Accordingly, the accepted upper and lower threshold are 2000 and 100 lux. We are interested in the lower level. We want to guarantee that, during the day, the unit always have a minimum of 100 lux of natural sun light. To do that, we consider the worst scenario during which we have a very low amount of solar gains and we want that, even in this case, when the DYN model decides to close the solar shadings as much as possible, the unit still has 100 lux of natural sun light. Having 100 lux of natural light means having roughly 0.79 W/m^2 from the sun. Considering the windows surface simulated in this study, this value becomes 0.0079 kW. The lowest value of solar gains happened to be during winter, for the North oriented unit. According to these two values, we find the minimum value of Δ to be 0.3.

The binary variable x_i connects the configuration of the shading system to the electricity final cost. When the shadings move, the binary x_i activates the parameter λ in the objective function, which represents the cost of this automation. In other words, when the blinds configuration during the period i is different from the one in $i-1$, x_i is equal to 1. When $x_i = 1$, the objective function accounts for λ. To choose the value of λ, we refer to a dynamic solar shading system in the market, which is called Cilium and it is produced by RENSON Manufacturers. This system is moved by a 230V motor which has a power consumption of 0.18 KW. Accordingly, we set $\lambda = 0.18$.

We add the following constraints to the PH model:

$$q_{sol,i} = \Delta_i \epsilon (q_{sol,B,i} + q_{sol,D,i}) \quad \forall i \in I \tag{6.1}$$

$$\Delta_i - \Delta_{i-1} \leq x_i \quad \forall i \in I \tag{6.2}$$

$$\Delta_{i-1} - \Delta_i \leq x_i \quad \forall i \in I \tag{6.3}$$

Where the Equation 6.1 represents the reduction of solar gains, due to the dynamic shading system. The other two equations 6.2 and 6.3 connect the binary variable to the status of the shadings: when the configuration changes, the binary has to be equal to 1.

Finally, the objective function becomes:

$$\begin{aligned} min \quad & \sum_{i=1}^{m} ((Q_{U,i}^H + Q_{S,i}^H + d_L^w + W_i^H + q_i^{fan,w})c_i^H + \\ & (Q_{U,i}^C + Q_{S,i}^C + d_L^s + x_i\lambda + W_i^C + q_i^{fan,w})c_i^C)) \end{aligned}$$

By way of example, if it happens that at 11 AM the shadings are totally opened but at noon the amount of solar gains makes the cooling be very expensive. Because of that, the DYN model decides to close as more as possible the shadings. By doing that, it will reduce both the amount of solar energy entering the unit and the final cost of cooling. From the mathematical point of view, this means:

$$i = 12$$
$$\Delta_{12} = 0.3$$
$$\Delta_{11} = 1$$
$$x_{12} = 1$$

Accordingly, the constraint 6.1 reduces the amount of solar gains of 0.30 and the constraint 6.3 activates the penalty λ in the objective function.

CHAPTER 7 MODEL VALIDATION AND PARAMETERS CALIBRATION

7.1 Model validation

In this chapter we show the validation of the SM model and we calibrate the input parameters of the three models. We validate the first of the three models showed in this study (SM) and we build the other two models (PH and DYN) on the base of the first. For sake of clarity, we call "SM-nonopt" the model which we are validating and "control" the model which we are using to compare it to.
To do that, we simulate the control unit with SIMEB energy software. We simulate a control unit per each orientations and for both winter and summer study cases. The validation is developed by comparing the SM-nonopt run without optimization (i.e as energy load calculator) to the control units. We simulate the two models under similar conditions and we compare their heating/cooling loads by using the ASHRAE's guideline 14. The guideline suggests two statistical indicators: the coefficient of variation of the root mean square error (CVRMSE) and the normal mean bias error (NMBE). The SM-nonopt is considered validated if $CVRMSE \leq 30\%$ and $NMBE \leq 10\%$, with hourly data, per orientation and for both winter and summer study cases. We run the SM-nonopt and the control during a period of two days, with the aim of reducing the eventual noise due to the choice of initial conditions. The validation is successful for all the orientations. We show the results in the following plots (Figures 7.1 and 7.3). We indicate the heating/cooling demand of the SM units and the control units with "Q_{SM}" and "Q_{DOE}" respectively. Tables 7.2 and 7.4, we report ASHRAE's statistical indicators, calculated to compare the SM-nonopt to the control.

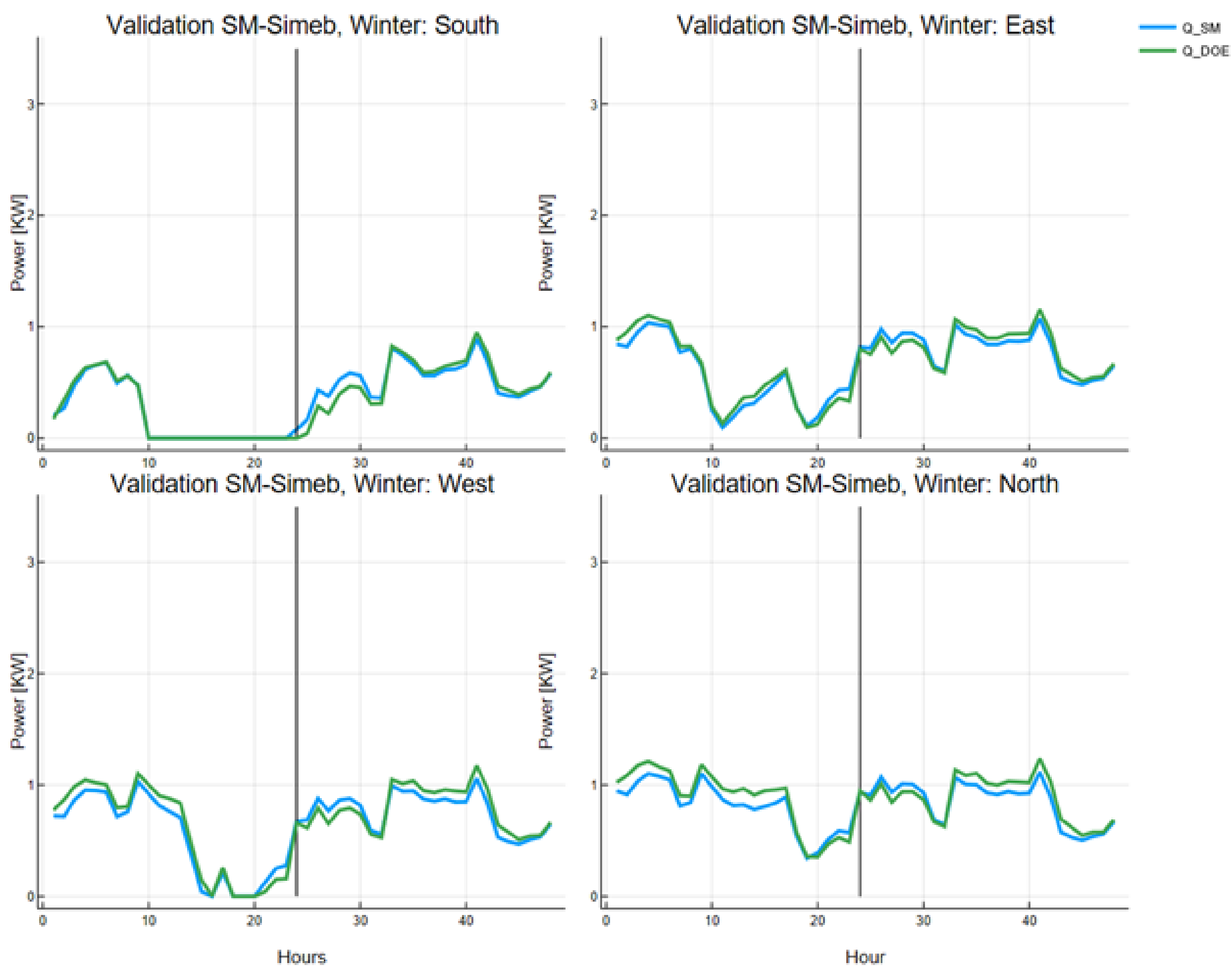

Figure 7.1 Validation of all the orientations, 2 days winter study case (Salerno, Ilaria 2019)

WINTER	**CVRMSE**	**NMBE**
SOUTH	7.96	0.65
EAST	4.52	1.58
WEST	6.11	2.64
NORTH	5.11	3.06

Figure 7.2 ASHRAE's statistical indicators calculated for winter study case, expressed in percentage (Salerno, Ilaria 2019)

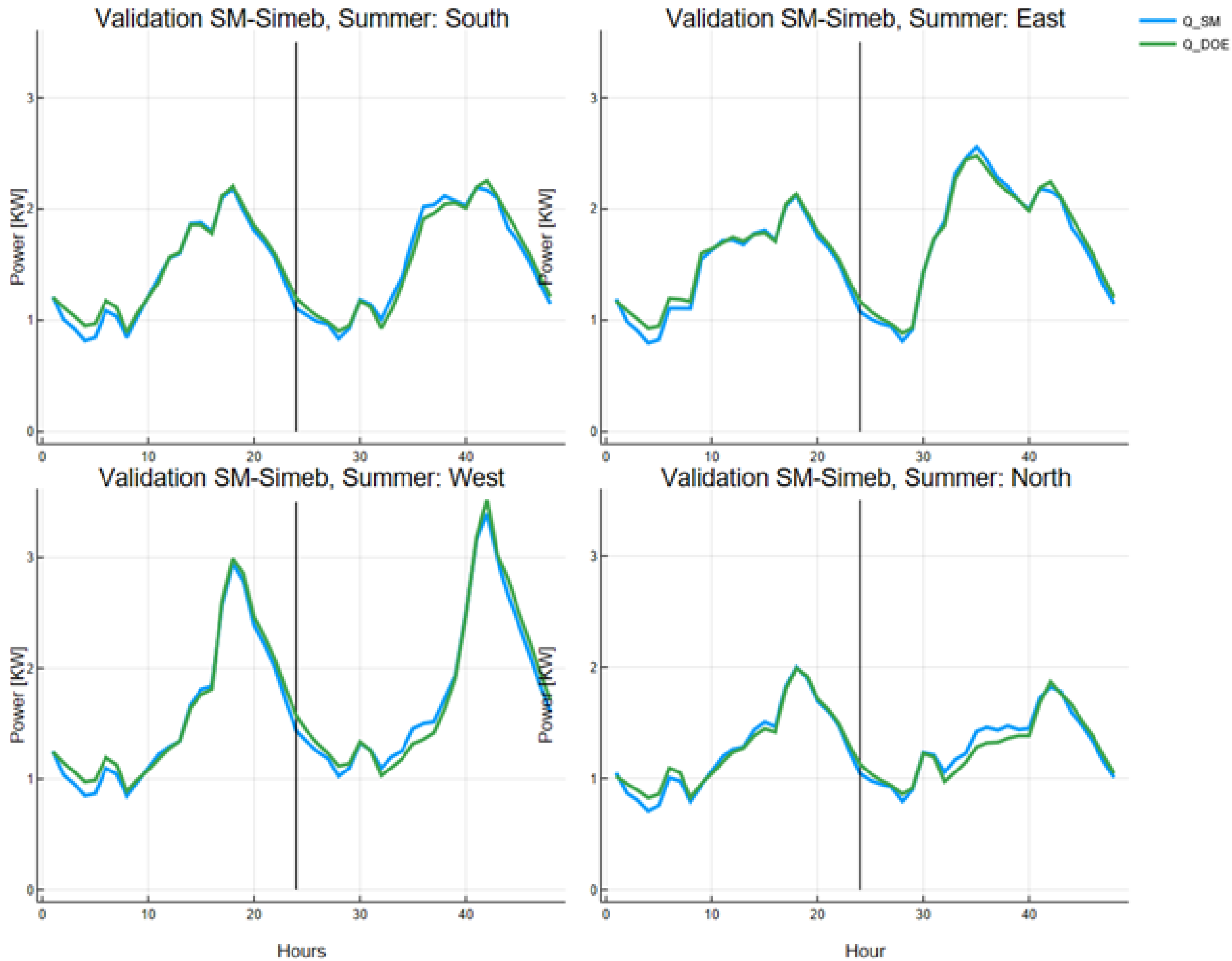

Figure 7.3 Validation of all the orientations, 2 days summer study case (Salerno, Ilaria 2019)

SUMMER	**CVRMSE**	**NMBE**
SOUTH	2.25	0.72
EAST	1.81	0.91
WEST	2.47	0.97
NORTH	2.61	0.02

Figure 7.4 ASHRAE's statistical indicators calculated for summer study case, expressed in percentage(Salerno, Ilaria 2019)

7.2 Study case

We assess four different orientations for the external façade. All the units are located in Montreal, so solar gains calculation is based on the parameters of this city. All the units are characterized by the same geometry: their floor space is $100m^2$, having a width of $10m$, a depth of $10m$ and an height of $4m$. They have only one external façade, as showed in Figure 4.1. That façade has two windows for a total of $10m^2$ of glass surface. The units considered in the PH and DYN models have the same technical features of those from the SM model but with an additional external glass skin. The external skin covers the entire surface.
The validation gives us the opportunity to calibrate the input parameters of the three models. Accordingly, we set the following calibrated parameters, obtained by the validation of the SM model with SIMEB: solar gains (Figures 7.5 and 7.6), internal gains (Figure 7.9), infiltration, lighting demand (Figure 7.10), weather conditions (Figures 7.7 and 7.8), technical features of the external wall and windows (Table 7.12).

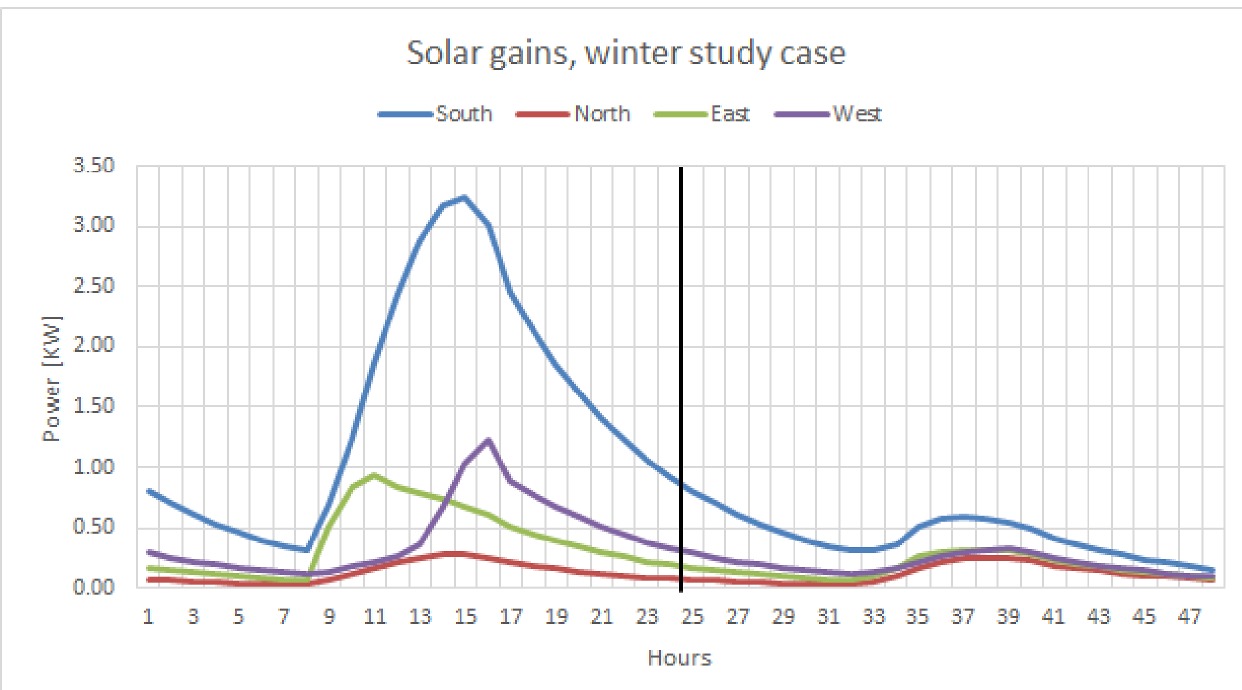

Figure 7.5 Solar gains per each orientation, winter study case

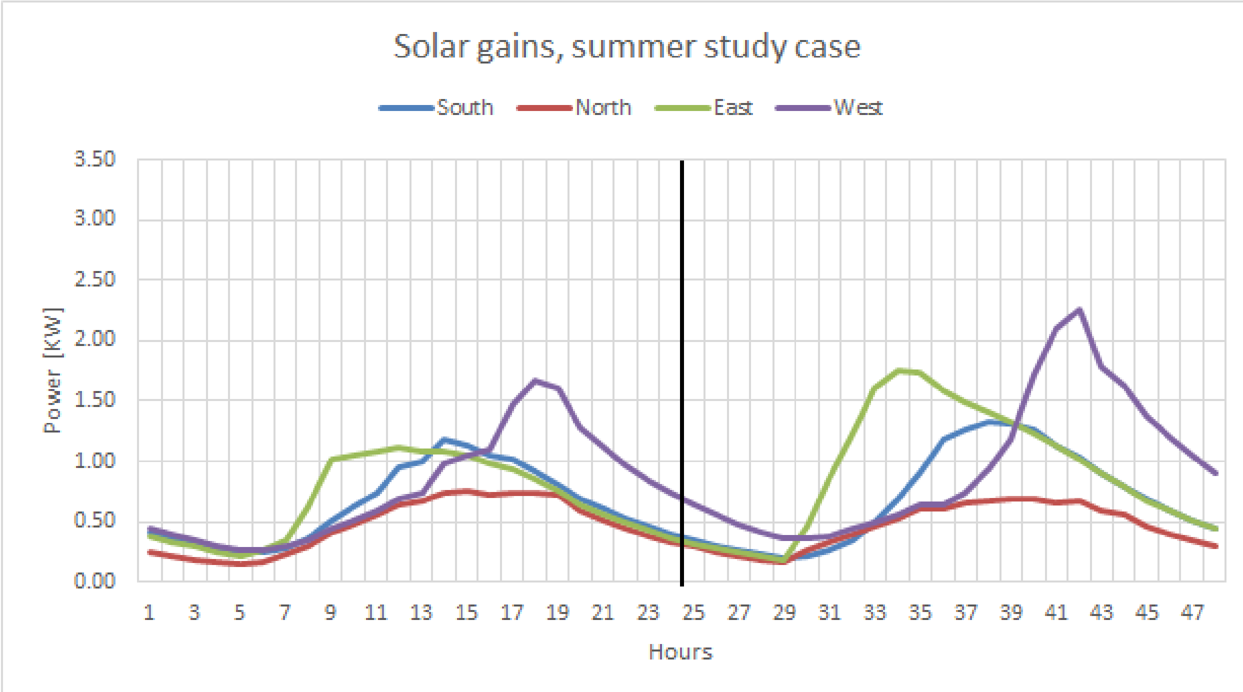

Figure 7.6 Solar gains per each orientation, summer study case

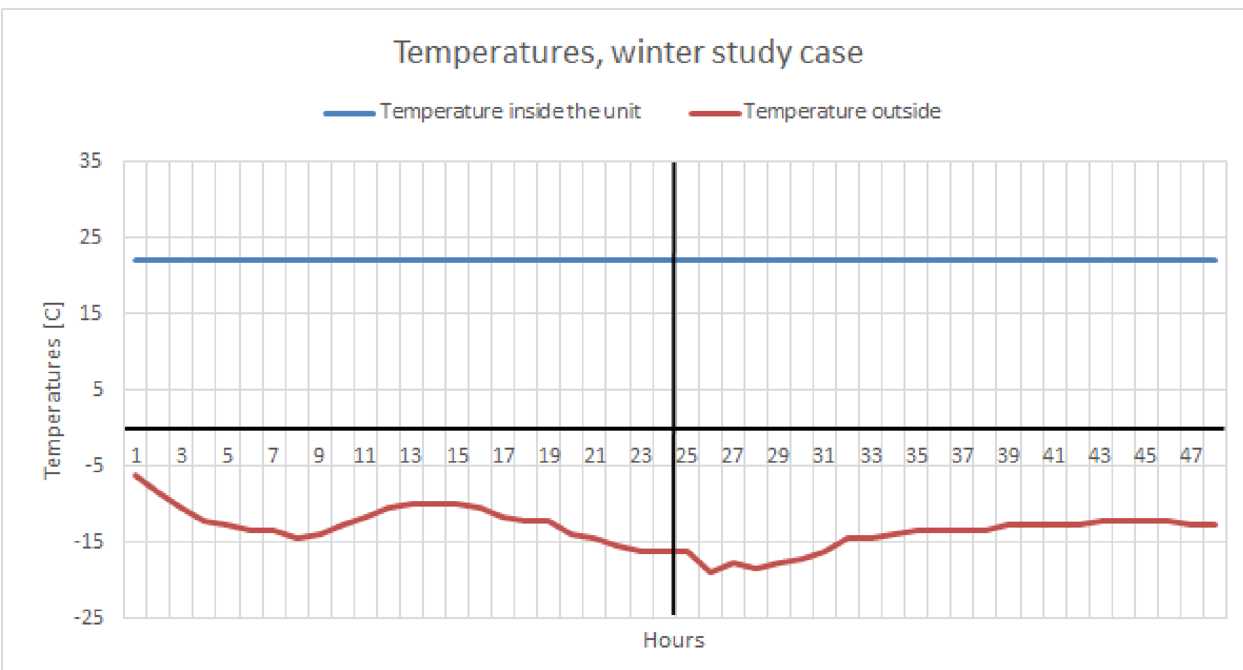

Figure 7.7 Temperatures for all the orientations, winter study case

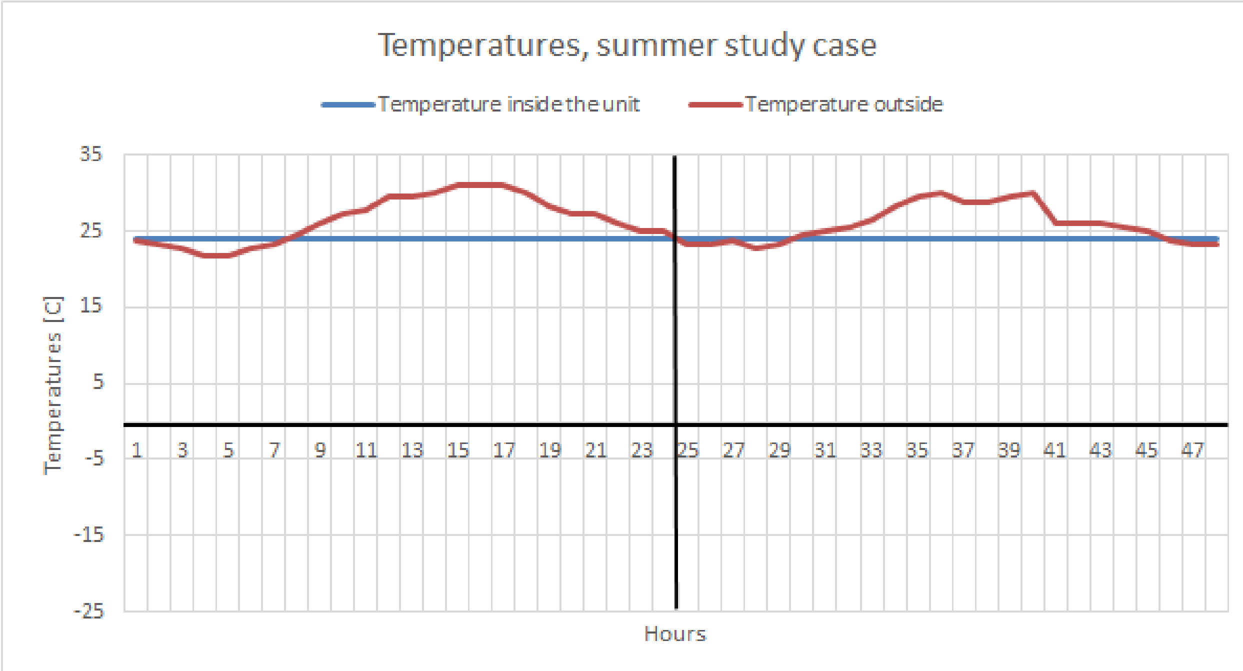

Figure 7.8 Temperatures for all the orientations, summer study case

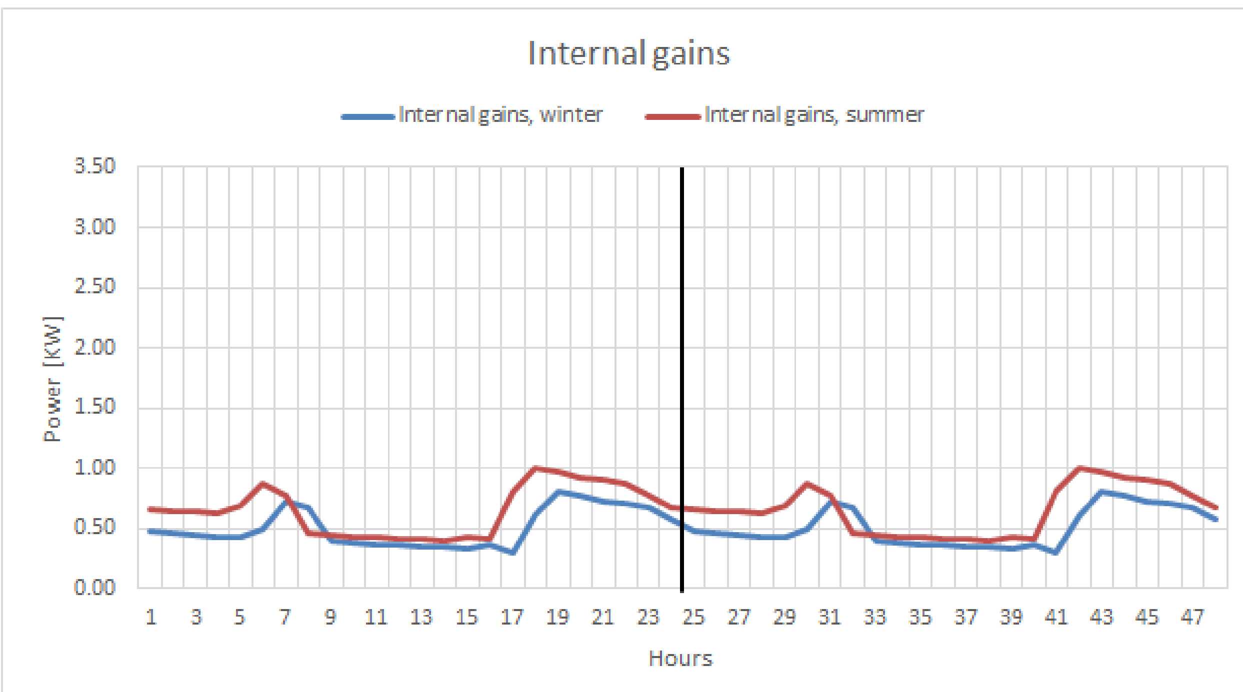

Figure 7.9 Internal gains for all the orientations

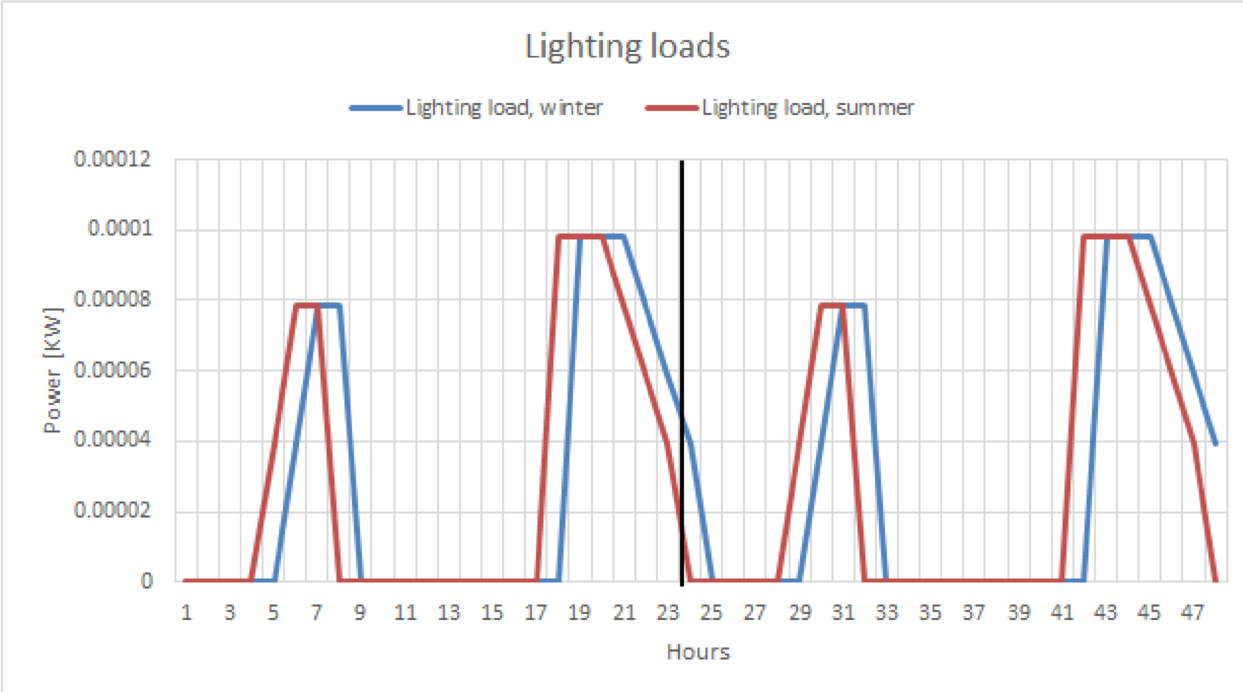

Figure 7.10 Lighting demand for all the orientations

Although the validation have been done accounting for a fixed temperature inside the unit, the three optimization models presented in this study benefit from the variation of the this temperature. We assume a comfort range inside the living zone that goes from 21°C up to 25°C and we enforce the optimization models to stay inside these boundaries.
As we said, all the models consider the Ontario Time-of-Use tariffs. The electricity cost during two working days is shown in Figure 7.11, for the winter and summer study cases.

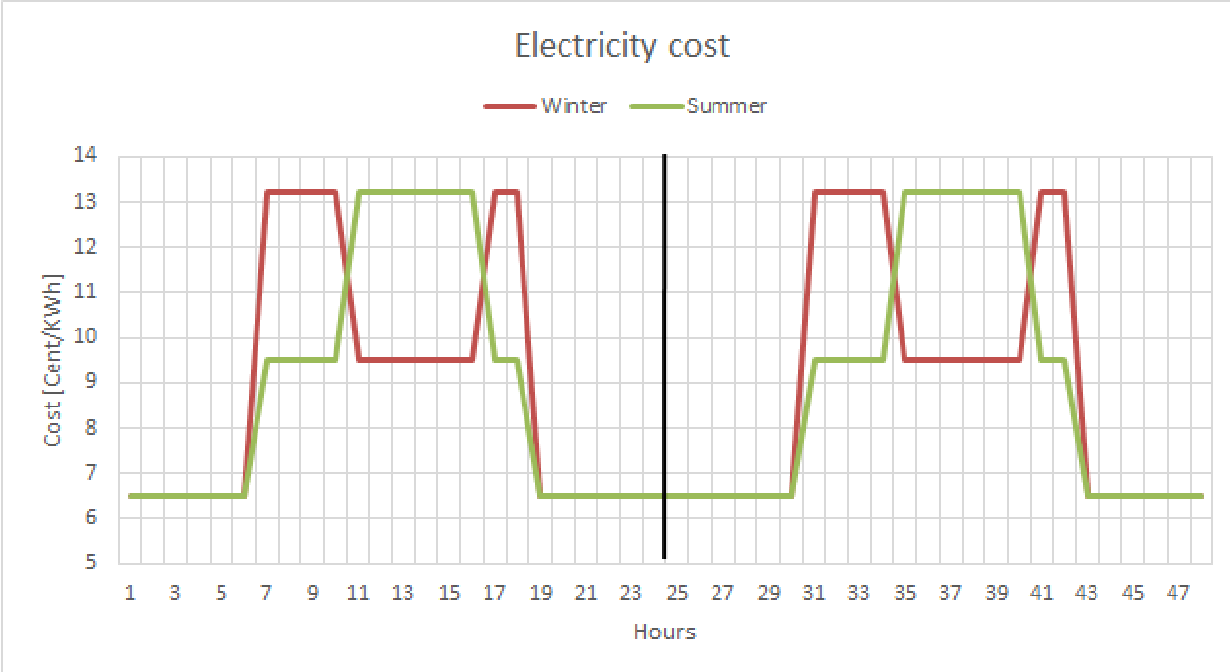

Figure 7.11 Ontario Time-of-Use

All the models and all the units have the same internal gains structure since for this study case, we are modelling only households. We account for two working days. Moreover, both internal gains and lighting load schedules, arise a cliff of one hour passing from the winter to the summer study case. This is connected to day-light saving time. We point out that the cliff does not affect neither the calibration nor the results of the models.
The external wall considered in the validation is taken from SIMEB energy software. It represents a common wall for residential buildings. It is constituted by four layers, each of which has the technical features shown in the following table.

		Total heat transfer, wall										
		Ck [kJ/K]	mk [kg/s]	Lk [m]	rho k [kg/m3]	cp k [kJ/kg K]	Rk [m2 K/kw]	Kk [w/m K]	hk [w/ m2 K]	l [m]	H [m]	A wall [m2]
	Ext						30.00		34			
Brick	k 4-5	1.62	1.76	0.10	2082.60	0.92	77.53	1.31				
Air	k 3-4	0.00	0.00	0.07	1.20	1.00	1556.63	0.04		10	4	30
Mat-EW-N.1	k 2-3	0.04	0.03	0.12	28.84	1.21	3570.38	0.03				
Gypsum	k 1-2	0.09	0.11	0.02	801.00	0.84	99.15	0.16				
	Int						120.00		8.29			
	Tot.	**1.75**	**1.90**	**0.31**			**5453.69**					

Figure 7.12 External wall technical features

Where we calculate the following parameters, with the aim of including the thermal mass and resistance of the wall into the three models:

- C_k : thermal capacity of the k-layer [kJ/K]

- L_k : thickness of the k-layer [m]
- ρ_k : density of the material composing the k-layer [kg/m^3]
- cp_k : specific heat of the material composing the k-layer [kJ/kg K]
- R_k : thermal resistance of the k-layer [m^2 K/W]
- K_k : conductivity of the material composing the k-layer [W/m K]
- h_k : global heat transfer coefficients from ASHRAE [W/m^2 K]
- l : total width of the unit [m]
- H : total height of the unit [m]
- A : surface of the wall [m^2]

Concerning the windows, we consider that they are characterized by the U-value of 3.52 W/m^2K. Moreover, the external skin of the models PH and DYN is equal to 1.8 W/m^2K. As we mentioned previously, solar gains are strictly related to the glass surfaces; in other words, the amount of solar gains captured by the two models, SM and PH, is different. While the SM model have only 10m^2 of windows to catch solar rays, the PH has the entire external skin to do it: we consider the 90% of the total vertical surface because of its frame, so we account for 36m^2 of glass surface. Accordingly, the PH benefits more from the thermal energy of the sun. Because of that and of its improved thermal insulation, the PH has lower energy consumption and cheaper final cost than the SM. The amount of solar gains caught from each unit, during a summer and winter day-type is represented in Figure 7.13. In the same figures, we also point out the on-peak period: it is possible to identify the units that can bring more benefit from their orientation. In the same way, it is possible to see the units with higher cost. The East oriented unit happens to be the most expensive during summer. Looking at the plots, it easy to see why: this unit has its solar energy peak exactly during the on-peak period. Because of that, its cooling system has to work more during the most expensive hours to guarantee thermal comfort.

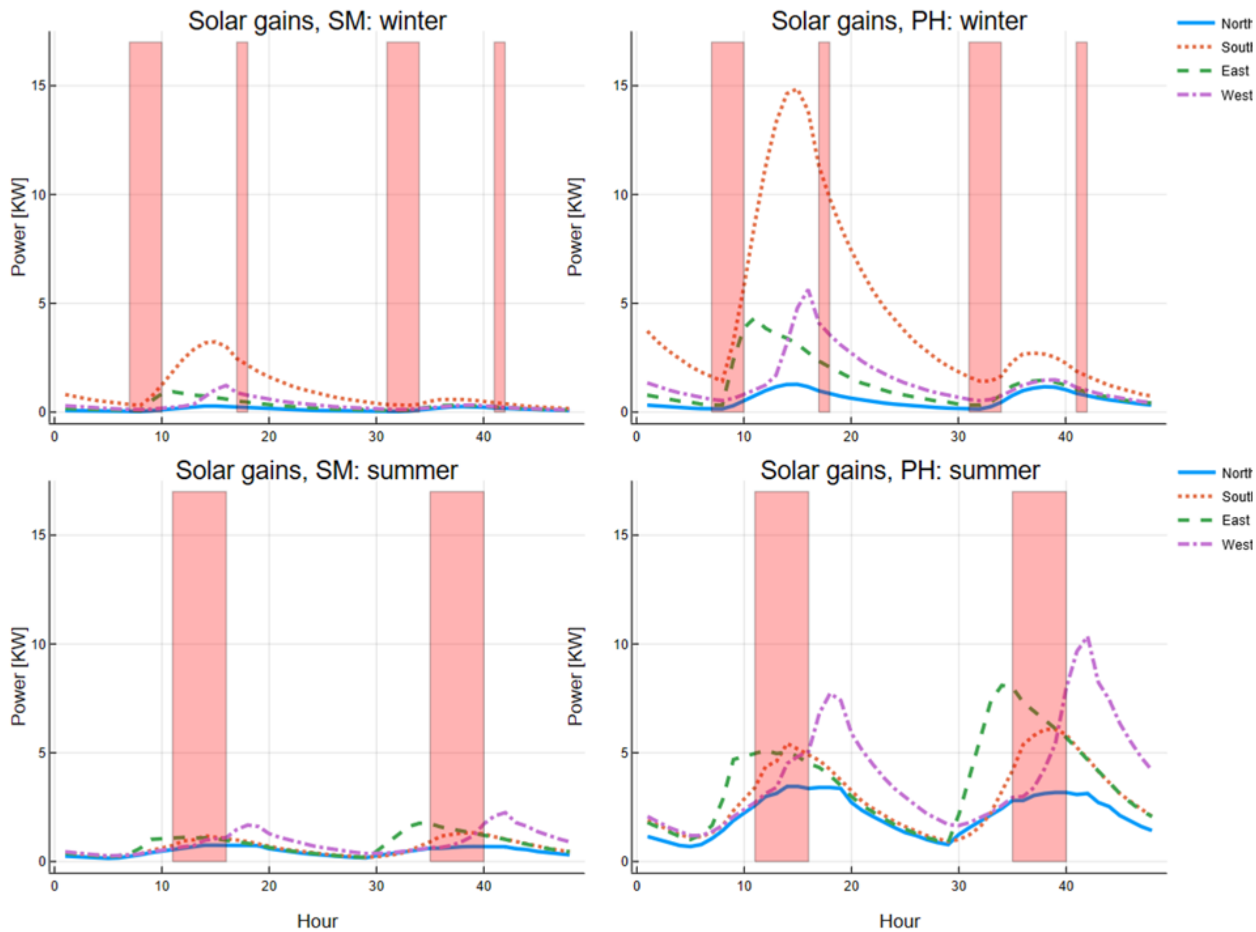

Figure 7.13 Solar gains during winter and summer for SM and PH models

Furthermore, the PH and DYN models have lower infiltration and transfer losses than the SM. In fact, they are directly related to the difference between the indoor and outdoor temperatures. In the PH and DYN models, the average temperature of the air inside the cavity of the double façade is closer to the temperature inside the living zone, than the temperature outside.

CHAPTER 8 STUDY CASE: RESULTS ANALYSIS

In this chapter we show the results of the three models presented. We will compare a traditional apartment to its "smart version", having the SM model acting as energy management system. After that, we will compare the results of the SM model to the PH one. Finally, we will show the comparison between the PH and the DYN models. At the end of the chapter we compare the final energy cost per each model, per each orientation, for the winter and summer study cases.

8.1 SM opt. vs SM non opt.

In this section we present the results for 48 hours experiments for the four orientations. We compare the SM model run without optimization to the SM optimized. The aim of this section is to asses the impact of having an energy management system that optimizes the energy consumption.

8.1.1 Winter

The results show that the energy management system can significantly reduce the final cost of energy, through power management. Nevertheless, the total energy consumption does not really change. In fact, the SM model benefits from timing: it overheat the unit before the on peak hours and during them, it warms the unit by using the heat previously stored (see Figure 8.1). This strategy allows the user to reduce the electricity bill but it can represent an issue for the grid operator. In fact, the fluctuation in the electricity demand increases, even though it is mostly predictable because it is connected to the type of unit (i.e residential). To tackle this problem, one option consists in reducing the final energy consumption. We will show within the following sections that the other two models reach this goal.
All the units benefit from the SM model, although their energy consumption is different. In fact, during the first day, the south oriented unit can totally cover the second energy peak by using its solar and internal gains. The west oriented unit needs to buy electricity during the same energy peak but its energy demand during the second half of the first day is lower than the one of east and north oriented units. Accordingly, the orientation of a unit impacts the magnitude of its energy consumption as well as the shape of its power demand profile.

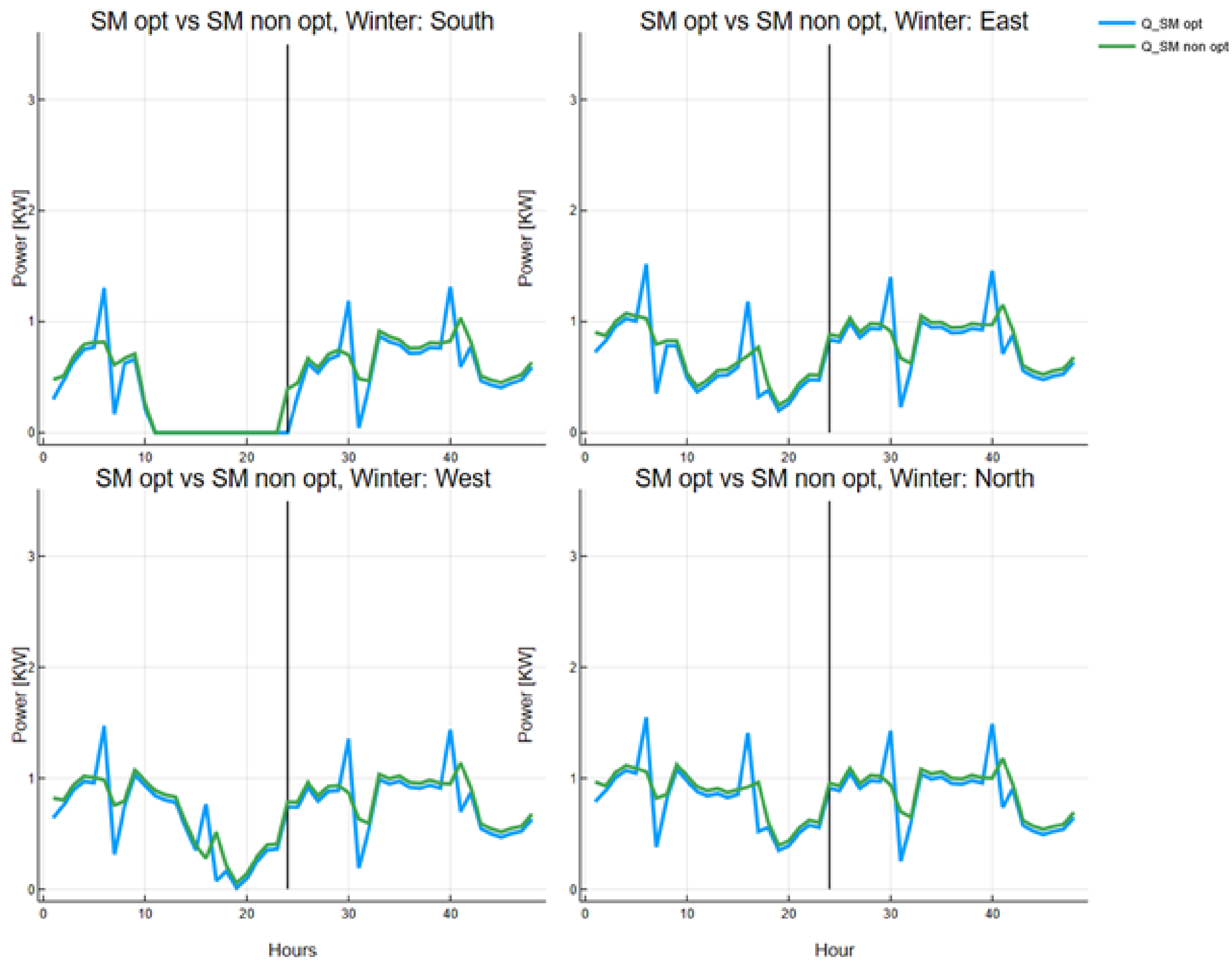

Figure 8.1 Heating energy demand of traditional units (SM^{nonopt}) and smart units (SM^{opt})

8.1.2 Summer

During summer, the optimized model runs similarly to the winter study case: the energy system still benefits from using the unit as storage (see Figure 8.2). The largest part of the energy demand of traditional units arises during the second half of the days. On the other side, the optimized units try to shift part of this amount toward the first half of the day. By doing that, they are able to reduce the final cost.

The unit with the highest energy cost happens to be the east oriented one. In fact, its solar gains peak arises just during the most expensive hours (see the curve of solar gains represented in Figure 7.13).

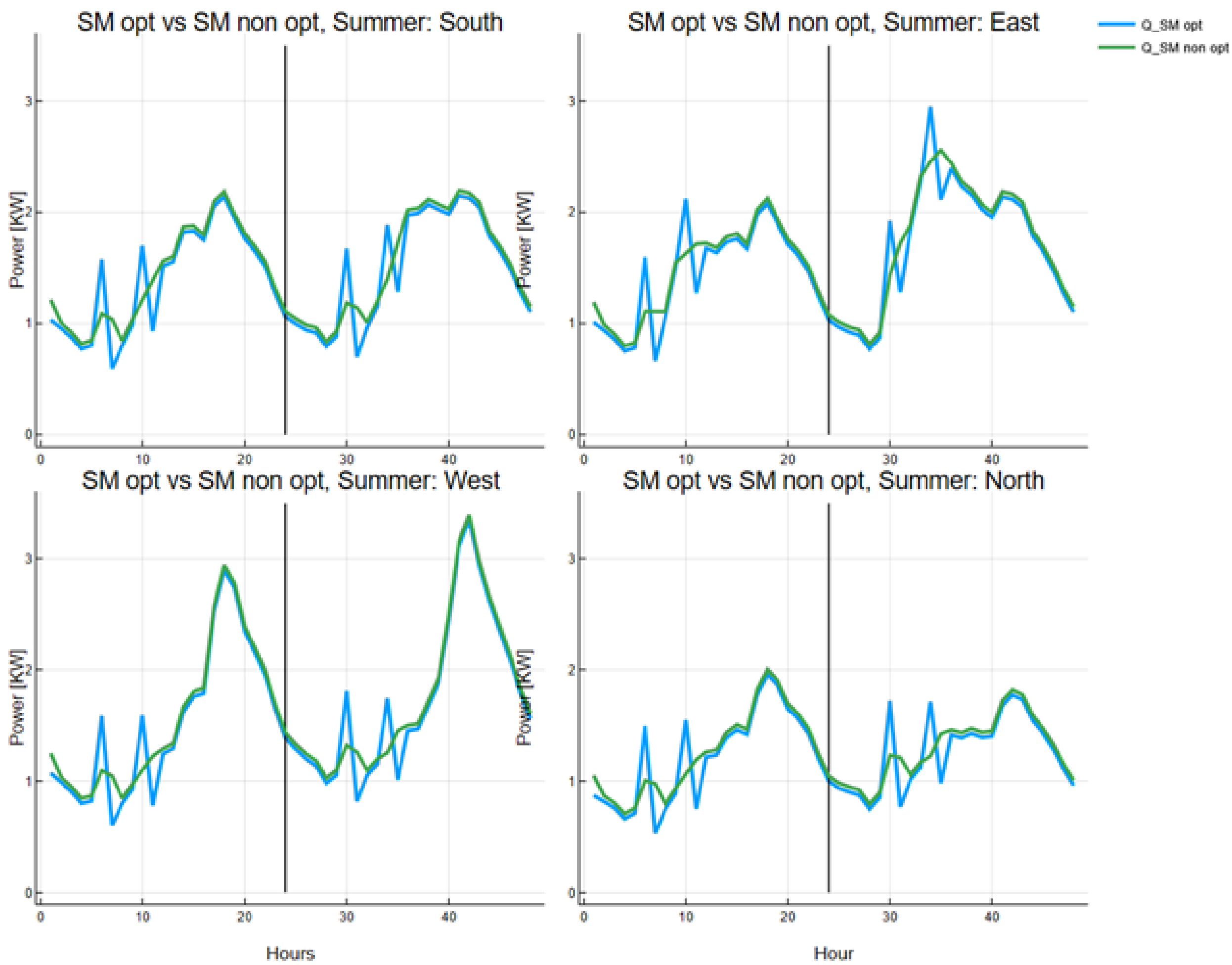

Figure 8.2 Cooling energy demand of traditional units (SM^{nonopt}) and smart units (SM^{opt})

8.2 PH vs SM

In this section we present the results for 48 hours experiments for the four orientations. We compare the SM model (i.e the "smart home" discussed in the previous section) to the PH model. We show two versions of the PH models: without and with heat pump cycle.

The only source of energy of the SM models is the power grid. The PH model has three options to satisfy the demand. During winter, it can buy electricity from the grid, it can use solar gains stored inside the storage-cavity, which naturally flow from the hottest toward the coolest reservoir, or it can use the heat pump cycle. The results of the optimization show that the cheapest source for the unit is to use the heat pump cycle.

The main advantage of the PH model is the total energy reduction. The PH model can not only reduce the final electricity bill but also decrease the amount of energy bought from the

power grid. Consequently, the PH model represents an interesting tool for the grid operator. In fact, the PH units happen to have lower energy peaks in their daily demand. Moreover, the PH model with heat pump cycle significantly reduces the demand fluctuation.
The PH model represents a smart house because it is designed in a smart way. With the SM model we showed that the natural capability of a unit to act as a thermal battery can be optimized. Now, with the PH model we demonstrate that this capability can be improved by the simple building design.

8.2.1 Winter

The PH model without heat pump reduces the energy demand for heating of the unit while keeping, mostly, the same curve shape of the SM model (see Figure 8.3). This is due to two main reasons. Firstly, the ability of the PH to capture more solar gains throughout the double façade. In fact, the amount of energy captured from the sun depends on the glass surface, which is larger in the PH model. This energy enters the double skin and it is stored inside its cavity. It warms up the envelope of the unit, so the temperature inside the storage increases during the solar gains peaks hours (see blue dotted curve in figure 8.3), while the energy bought from the power grid decreases (see blue solid curve in figure 8.3). This brings to the second reason which makes the PH model be cheaper: the envelope of the PH units is more insulated. In fact, not only the external skin represents an additional thermal resistance for the transfer losses flowing outside the unit, but the air cavity is also warmer than the outside.
The storage capacity of the SM units is limited, first of all, by the user's comfort. It can store energy as long as the temperature inside the living zone is in the comfort range of 21 - 25° C. For the PH units, on the contrary, the storage behaviour is increasing only the temperature inside the façade and this threaten less the comfort of the user inside the living zone. By doing that, the PH units bring more advantages from the storage behaviour and the energy management system than the SM ones.
All the units benefit from the double façade, especially the south oriented one, which receives the largest amount of energy from the sun.

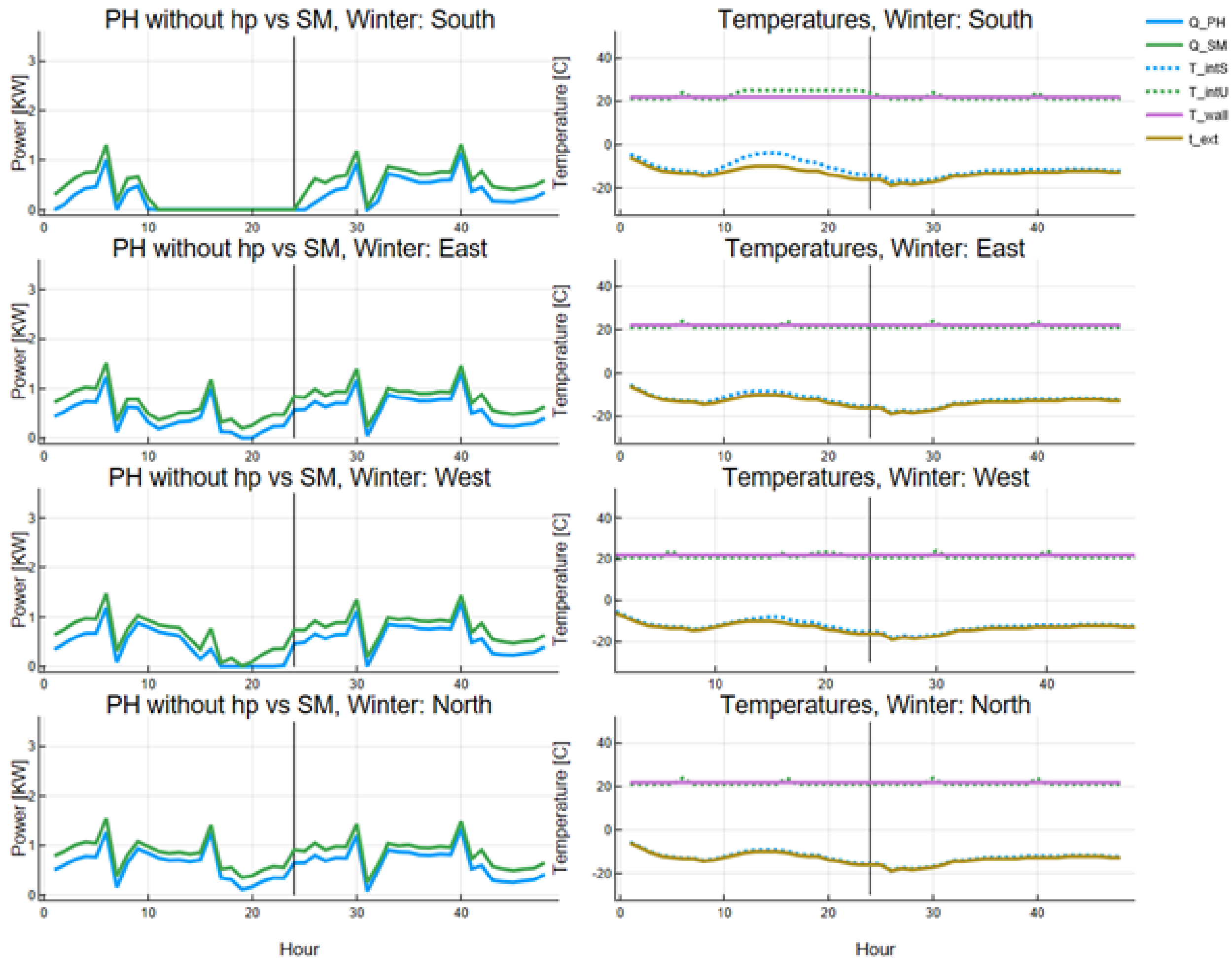

Figure 8.3 On the left, heating energy demand of SM units and PH units without heat pump cycle. On the right, temperatures of PH model

The air cavity inside the double façade, acts as three different elements: as thermal storage, as insulation and as hot reservoir for the heat pump cycle. As shown in Figure 8.4, the PH units having the heat pump cycle, do not buy electricity for the heating system (blue curve): they only buy the energy required to run the heat pump (purple curve on the left column). Moreover, the heat pump cycle acts between the air cavity and the living zone of the unit. This solution is more convenient than having the heat pump running between the outside and the living zone, because the air cavity is warmer than the external environment.

The PH model with heat pump happens to be the best solution among all the models, during winter. In fact, the DYN model brings advantages during summer, while it is mostly equivalent to the PH model during winter.

We stress out the relevance of the PH model for the power grid operations. As we said, it significantly reduces the demand fluctuation by decreasing the peaks during the day. Moreover, it makes the units behave similarly. In fact, Figure 8.4 clearly shows that also the north oriented unit does not need to buy electricity during the first day: even if the amount of solar gains captured by the north façade is very low, the user is able to profit from that. The north oriented unit, which was always the most expensive during winter, arises to be the most convenient orientation: it behaves well during winter and it is the cheapest orientation during summer.

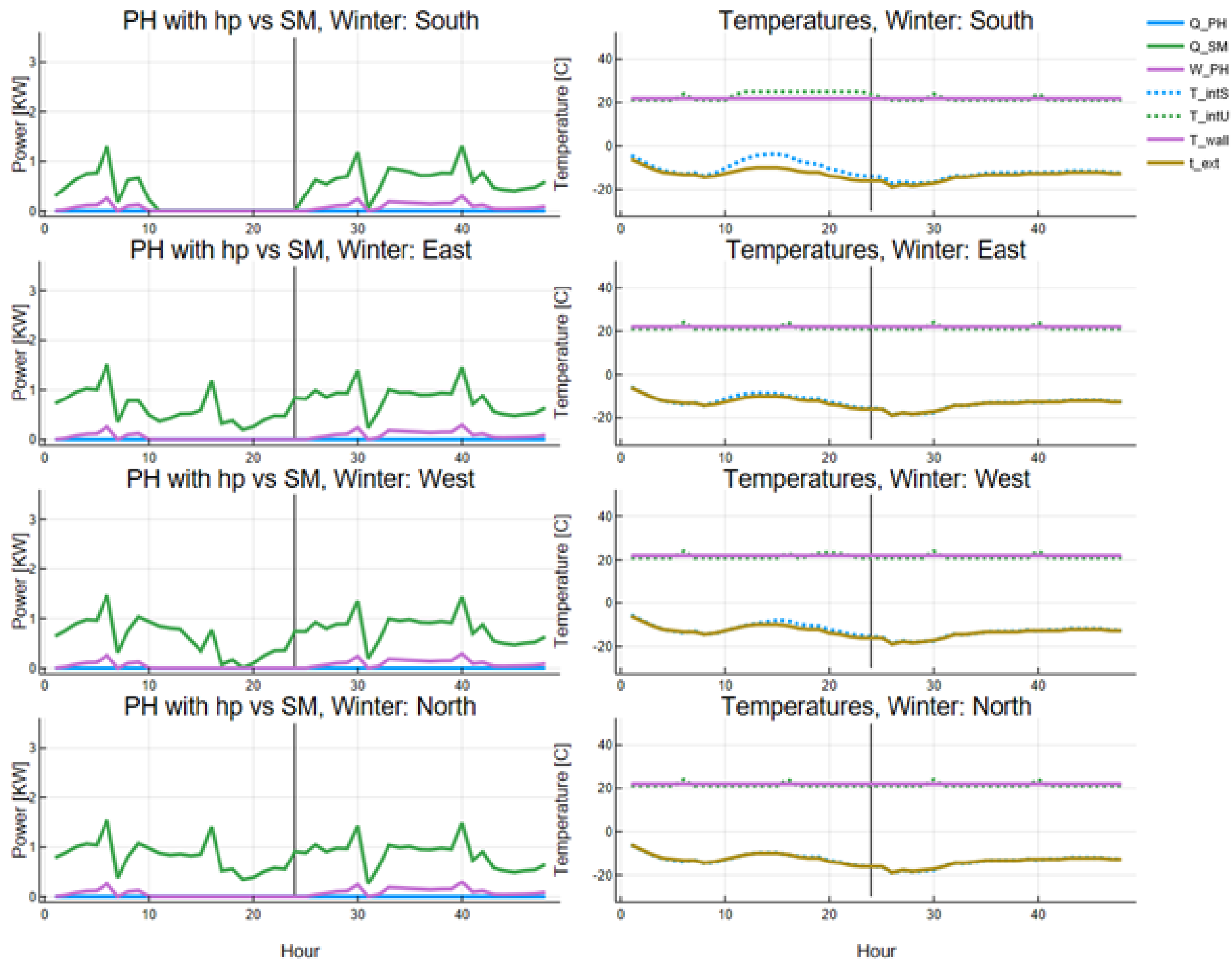

Figure 8.4 On the left, heating energy demand of SM units and PH units with heat pump cycle. On the right, temperatures of PH model

The temperature inside the storage-cavity acts differently in the two PH models with and without heat pump cycle. In Figure 8.5, we point out this phenomenon by taking the south oriented unit by example. The temperature inside the cavity of the PH model with heat pump is always lower than the temperature of the PH model without heat pump cycle. In fact, the heat pump moves heat from the storage (cold reservoir) toward the living zone (hot reservoir). By doing that, the temperature inside the storage-cavity decreases. During the daylight of the first day analysed, the two temperatures act in the same way. Looking at the plots in Figures 8.3 and 8.4, it is possible to understand why. The south oriented unit, indeed, is not buying electricity to warm the living zone during those hours: it has solar gains enough and it does not need to run neither the heat pump cycle nor the heating system.

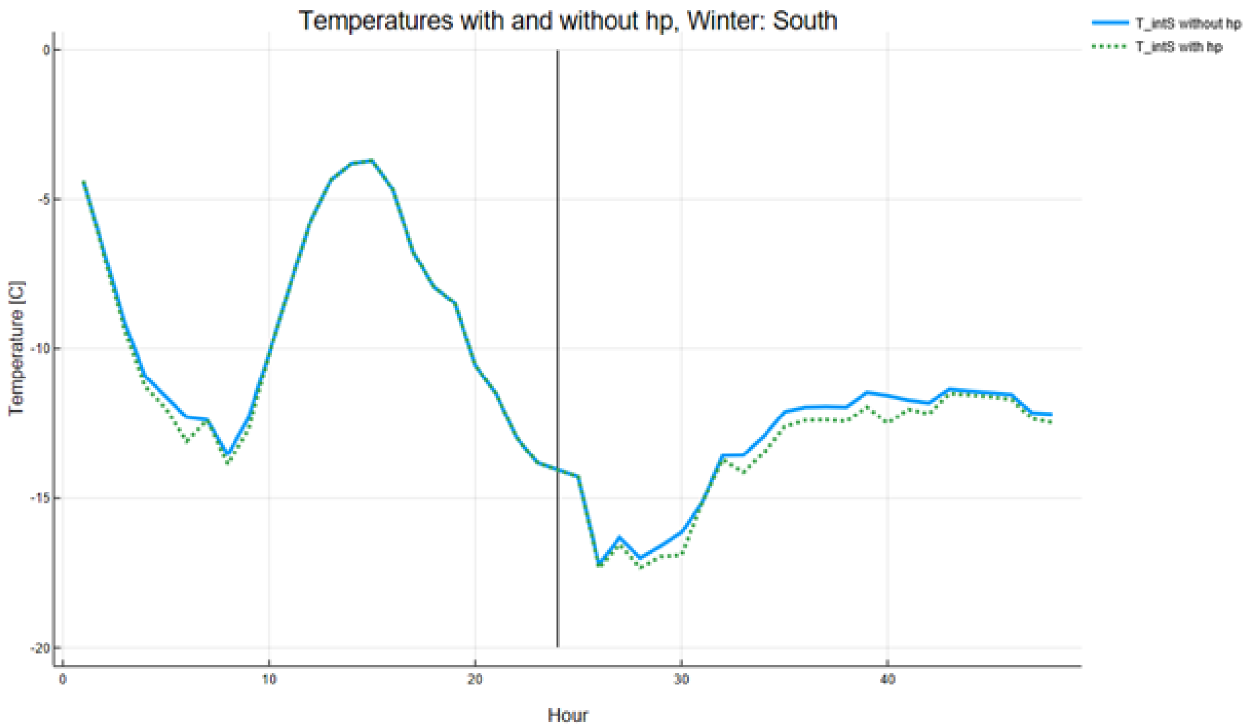

Figure 8.5 Comparison between the temperature inside the storage-cavity of the PH model with hp and the PH model without hp

8.2.2 Summer

During summer, the PH model without heat pump acts as the SM model (see Figure 8.6). The cavity of the double façade is warmer than the outside but this does not excessively penalise the final cooling consumption of the unit. In fact, the PH units still have an improved insulation because of the additional external skin.

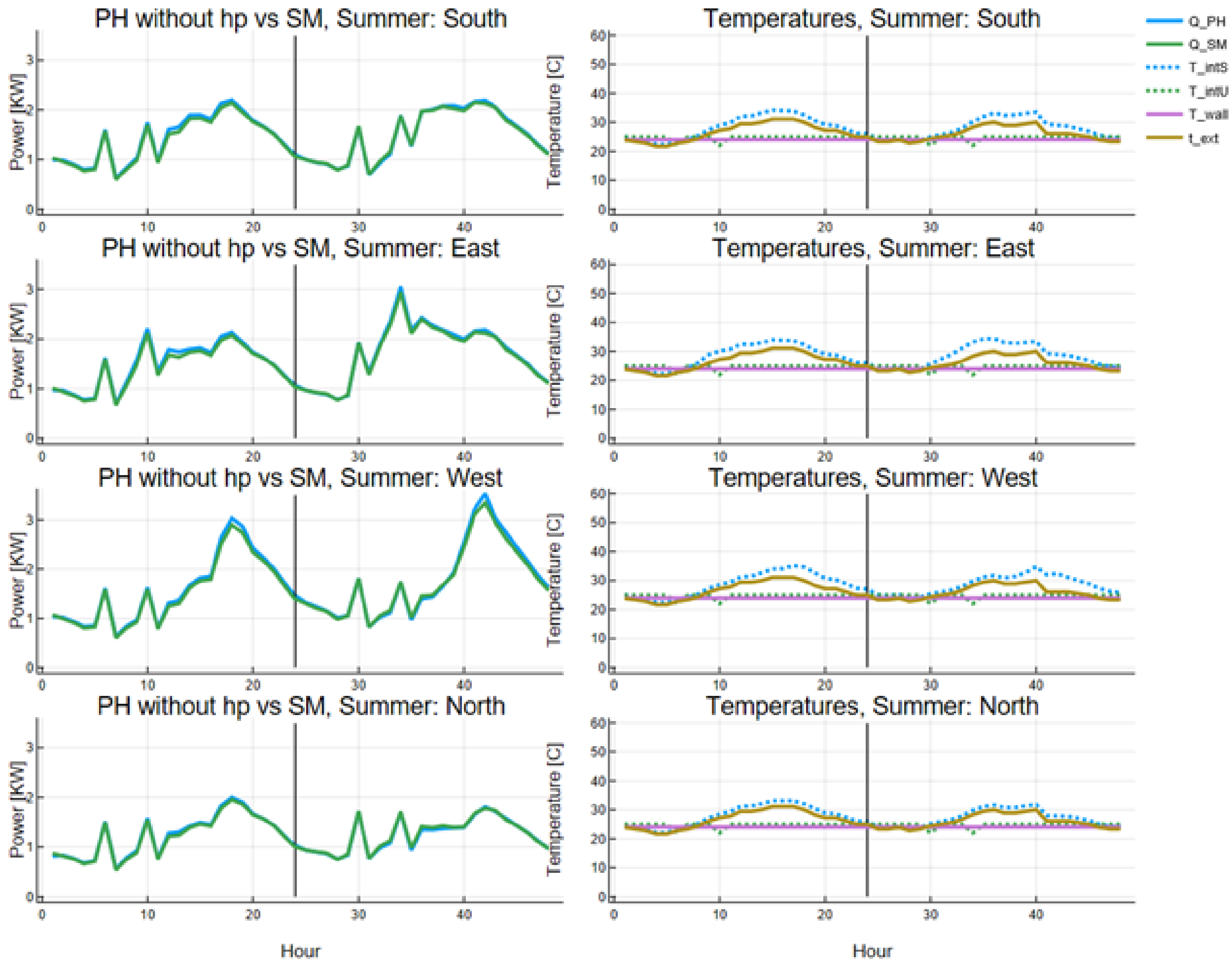

Figure 8.6 On the left, cooling energy demand of SM units and PH units without heat pump cycle. On the right, temperatures of PH model

Adding the heat pump cycle to the PH units does not bring particular benefit to the users, as it happens during summer (see Figure 8.7): during summer the PH model acts as the SM model. Further studies about air conditioning are addressed to future work.

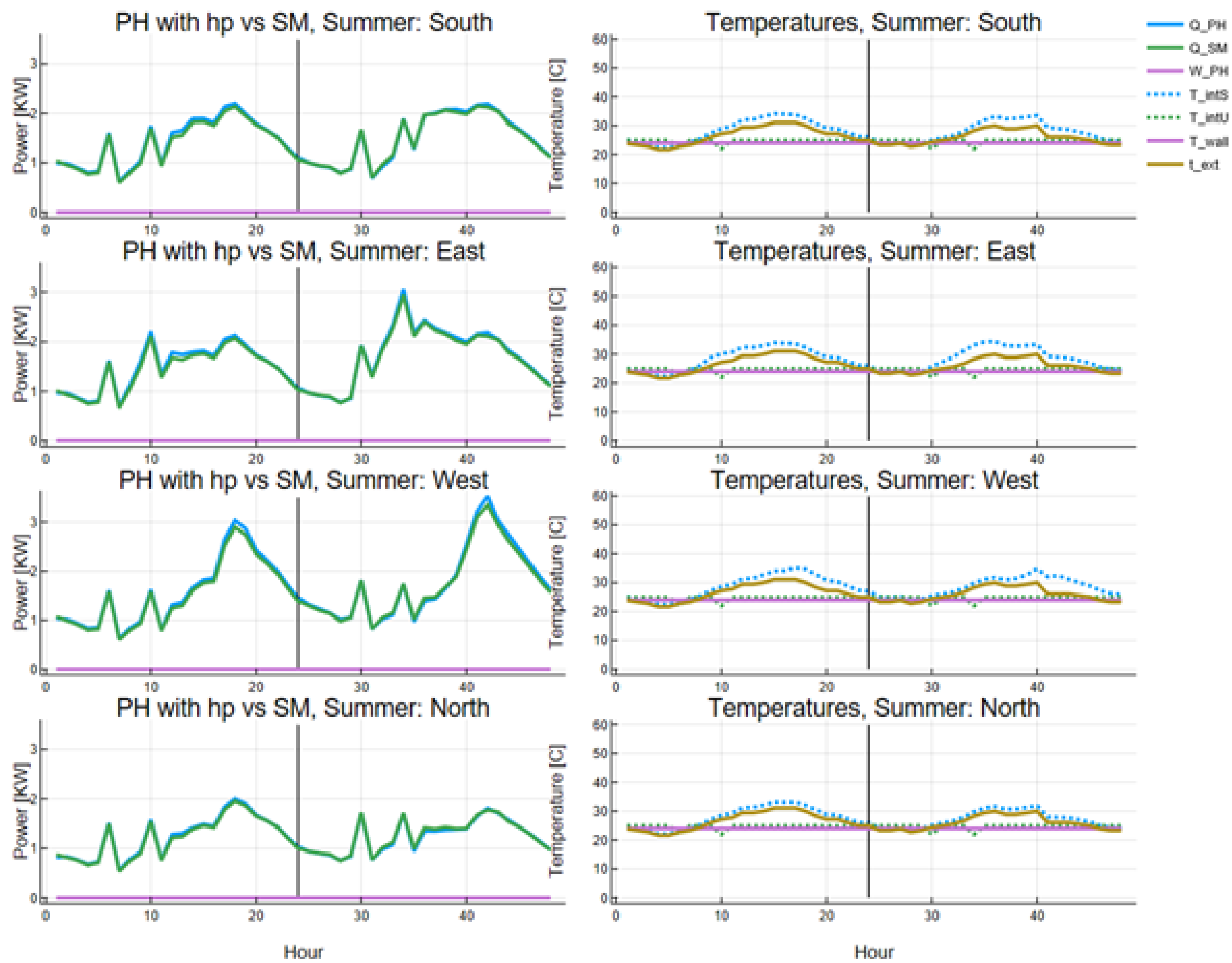

Figure 8.7 On the left, cooling energy demand of SM units and PH units with heat pump cycle. On the right, temperatures of PH model

For a future work, it is interesting to focus on the complementarity between the west and east oriented units. In fact, they behave in a complementary way: their cooling demand peaks arise during their solar gains peaks. For the east oriented unit, this happens during the first half of the day. On the contrary, for the west oriented unit, this happens during the second half. Connecting their storage-cavities can represent an interesting way to reduce the total demand fluctuation. The same idea can be applied to units having different activities inside, because they will also have different demand curves.

8.3 DYN vs PH

In this section we present the results for 48 hours experiments for the four orientations. We compare the dynamic model (DYN) to the PH one. As we previously stated, the DYN model represents a powerful tool for the cooling demand, although it does not effect the heating demand. During summer, the DYN model significantly reduces the cooling demand, in comparison to the PH model with heat pump. It represents the best option among all the models for the summer study case. In fact, final electricity cost, energy consumption and power peak demand are reduced.

The dynamic façade, because of its shading effect on the direct radiation when necessary, makes more homogeneous the amount of solar gains captured during the days; in other words, it reduces the solar gains energy peaks, only when it is more convenient for optimization purposes. The action of reducing solar gains, has the positive effect of diminishing the fluctuation in the electricity demand curve during the day. This last aspect is very important for the Utility side, since it can help them to manage the typical fast increasing of the electricity demand, just before the on-peak hours.

The DYN model's advantages are mostly related to the solar gains: the warmer is the weather, the greater economical benefit the dynamic façade brings to the user. Because of that, the dynamic system happens to be more interesting for the user who lives in a warm climate, where the amount of solar gains is relevant.

8.3.1 Winter

During winter the DYN model acts as the PH model with heat pump. In fact, the optimal solution to reduce the heating cost is to capture the highest amount of energy from the sun. To do that, the model keeps the shading system opened. All the units behave in the same way: we show the south oriented unit by example in Figure 8.9. In the same Figure, we also represent the electricity demand due to lighting, which becomes a decisional variable for the optimization problem. Nevertheless, the lighting demand is far lower than the heating (or cooling) demand: it is nearly zero. Because of that, the DYN model does not bring any significant disadvantages in relation to the lighting cost during both the winter and summer study cases.

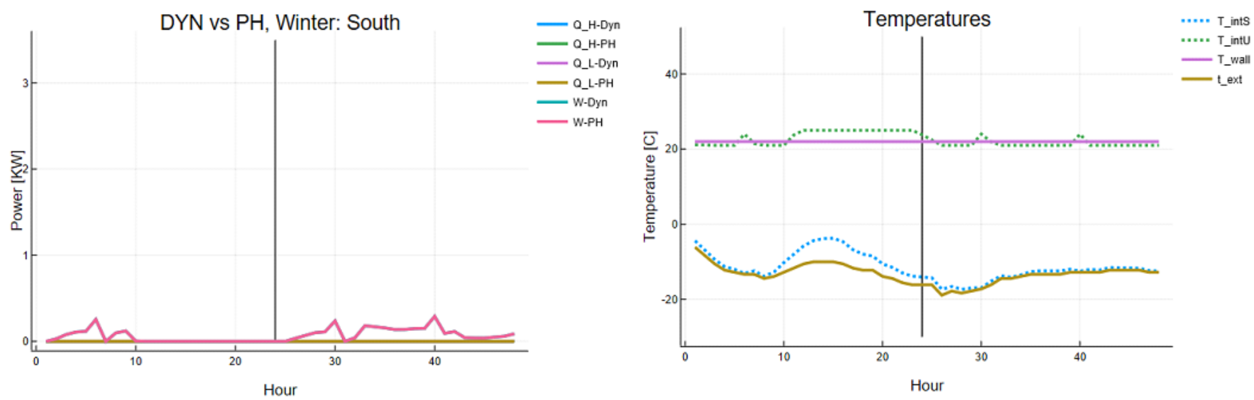

Figure 8.8 On the left, heating energy demand of DYN unit and PH unit with heat pump cycle. On the right, temperatures of DYN model

8.3.2 Summer

Figure 8.9 shows how the DYN model allows all the units to reduce cost, consumption and demand fluctuation during summer. The cooling system of the DYN units requires less energy than for PH units, because of the consumption reduction. Moreover, the temperature inside the air-cavity of the DYN units is lower than the one of PH units: transfer losses are reduced and the efficiency of the heat pump cycle arises.

For sake of completeness, we run also the DYN model without heat pump cycle. It brings important advantages, compared to the PH model without heat pump cycle. Nevertheless, energy savings are lower than the DYN model with heat pump. We show the results in the next section, where we compare all the models.

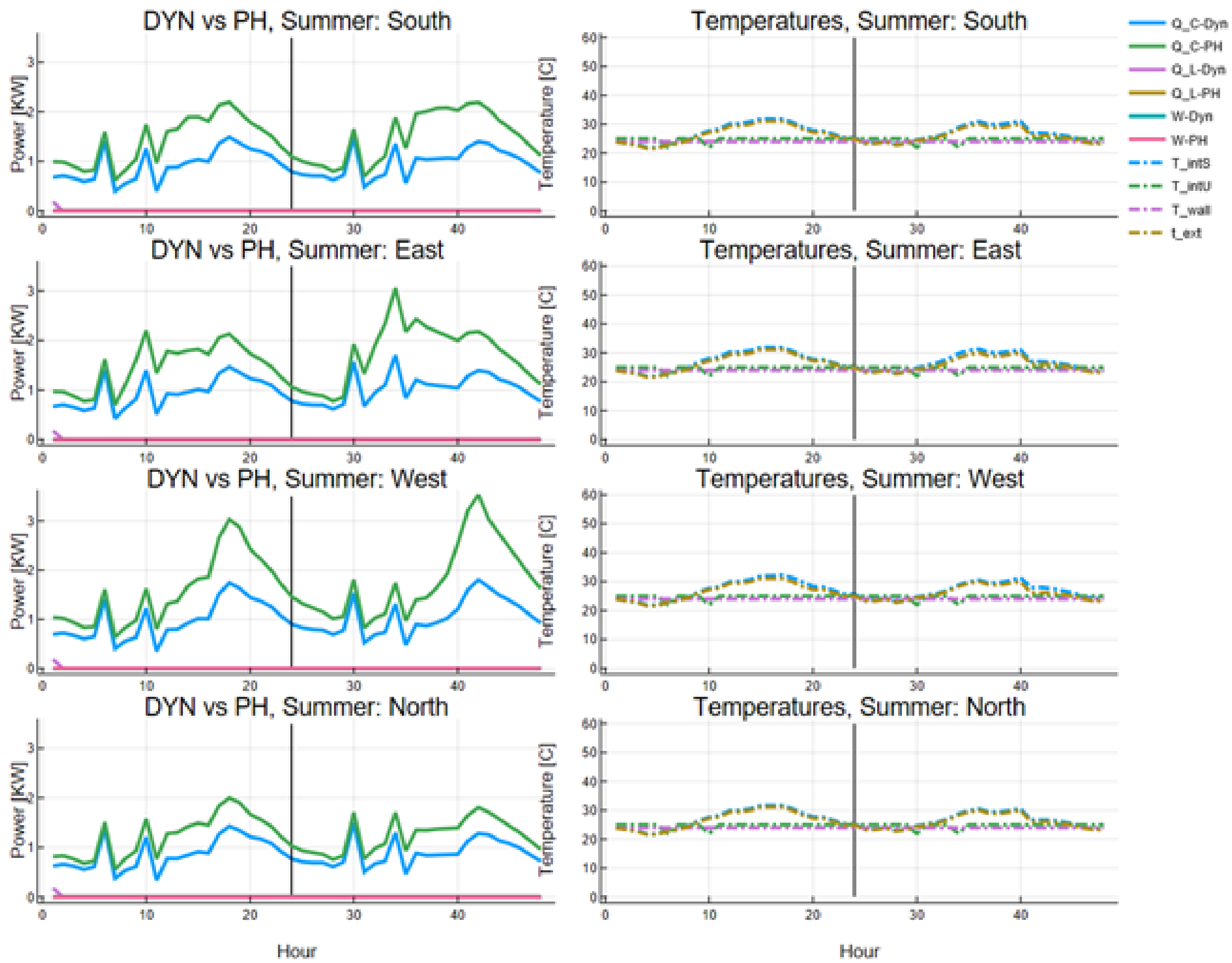

Figure 8.9 On the left, cooling energy demand of DYN units and PH units with heat pump cycle. On the right, temperatures of DYN model

During summer, the DYN model happens to be the best solution not only for the user but also for the grid operator. Moreover, the lower temperatures inside the storage-cavity reduce thermal stress on materials composing the façade. After running the dynamic model and analysing the results, we can suggest two types of shading systems: the louvres (see Figure 8.10) and the venetian blinds (see Figure 8.11), where the last one is less heavy and expensive. Moreover, the results show that the orientations have different needs. Accordingly, we suggest an horizontal shading system for the units on the south and north orientation and a vertical system for the units on the east and west. An example of this way of thinking is represented by the building designed by the australian solar system producer, Horiso [50].

Figure 8.10 Louvres system, Milstein Family Heart Center, New York, United States (Warchol, Paul. 2010)

Figure 8.11 Venetian blinds system, Torre Hadid, Milano, Italy (Salerno, Ilaria. 2017)

8.4 Cost comparison of the models

In this section we discuss about the final cost of heating/cooling and lighting obtained by the models. The standard house (represented by the SM non optimized) is compared to the SM model, the PH and DYN models with and without heat pump cycle. We evaluate the cost during two days, for all the orientations.

During winter the most expensive unit for all the models is the north oriented, as we expect. During summer, the units with larger consumption and energy cost are the East and the West. This happens because of two reasons; firstly, the direct component of the sun rays is more important for the East and West orientation since the sun is lower in the sky during the sunrise and sunset. Because of that, during these hours the temperature inside the living zone of the East and West orientations is higher than the one inside the North and the South ones. In fact, the dwelling on the South sees the sun only when it is high in the sky (during the middle of the day) and the unit on the North never sees it, so it does not receive the direct component of the sun rays. Secondly, the east and west units capture the highest amount of solar gains just during the on-peak hours, so the final cost is more expensive than the ones of the other two dwellings. Nevertheless, we will show that this difference among units' bills does not always have the same magnitude.

8.4.1 Winter

During winter, the PH model with heat pump cycle arises to be the best solution for the four orientations. In fact, the DYN model does not improve significantly the energy consumption. During winter, the south oriented unit benefits the most from the SM model: the final electricity bill in a smart house is 33% cheaper than in a traditional home. Also the other units profit from the energy management system of the SM model: the east and west units have their winter bill reduced by 21% and the north unit, by 11%.

The PH units have their electricity bill about 80% cheaper than the SM units and 84% cheaper than traditional units. If the same PH units do not use the heat pump cycle, their money saving is reduced to roughly 16% and 43% respectively. Passing from the SM to the PH model, brings more advantages to the north oriented unit; especially in the case without heat pump cycle, where the north unit still has the electricity bill 20% cheaper than the SM unit. In other words, passing from the traditional house to the smart one (SM model), brings more benefit to the south unit; although, passing from the smart model (SM) to the PH model, brings more benefit to the north unit.

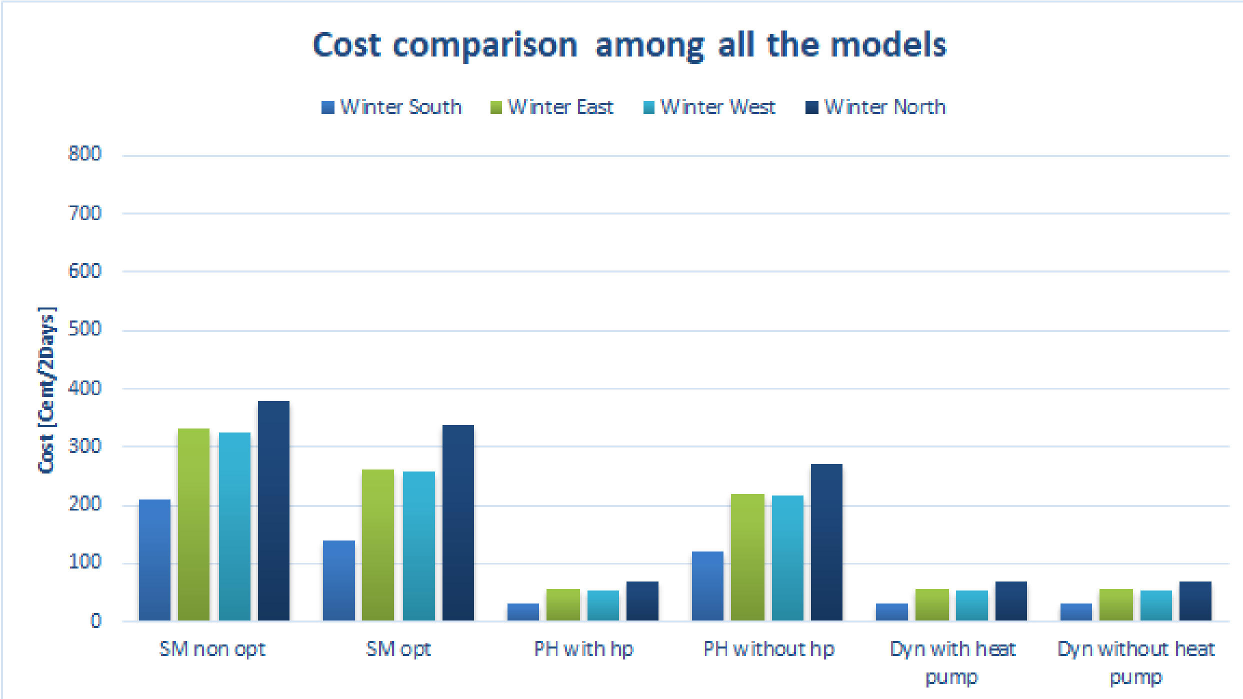

Figure 8.12 Comparison of the models for all the orientations, during winter

8.4.2 Summer

During summer, the best model happens to be the DYN. In fact, all the units reduce their summer bill by 40%, in comparison to traditional units. Moreover, the DYN model makes all the orientations act similarly: even if the north unit is still the cheapest one, the final bill does not vary significantly among units having different orientation.

During summer, the difference between traditional houses and smart homes is smaller: the SM units save only 3% on their final bill. Nevertheless, passing from the SM to the PH model with heat pump cycle does not lead to a significant gain for cooling needs. It is necessary to point out that both the PH models with or without heat pump cycle are equal or more expensive that the SM. In fact, the storage-cavity becomes warmer than the outside and this increases thermal reentry toward the living zone. Because of that, it is necessary to control the temperature inside the double skin. Forced ventilation could represent a valid way to tackle the problem.

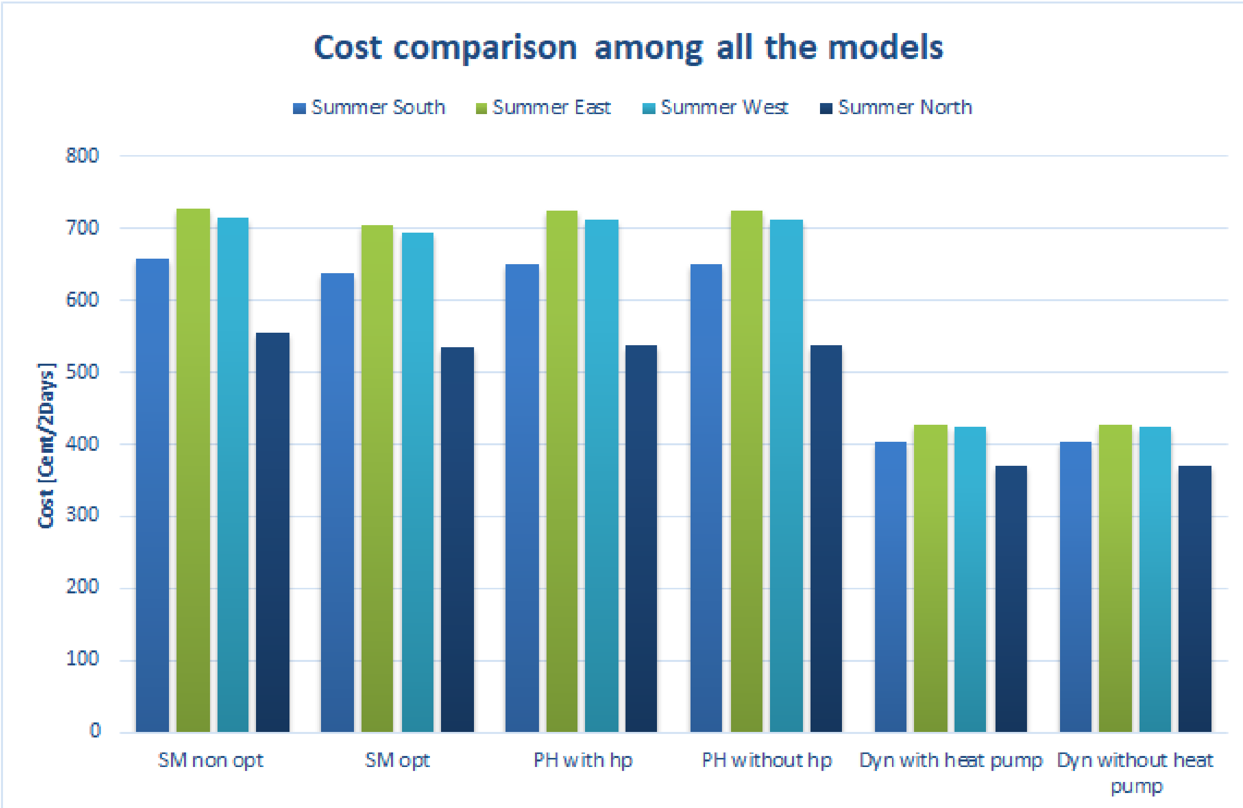

Figure 8.13 Comparison of the models for all the orientations, during summer

8.5 Cost variation according to the internal temperature set point

The temperature inside the living zone ($T_{U,i}^{int}$) is one of the most important decision variables for the optimization problem. It affects both the amount of energy to be bought from the public grid, the losses for ventilation and the losses for heat transfer. This temperature has to stay within a set point range that the user chooses. In other words, if during winter he is ready to lower the temperature range, he can save money. For the summer case the savings comes from increasing the upper limit of the temperature range.

In this chapter, we want to answer to two main questions: firstly, how much can the user save, by moving from his comfort zone? Second, does changing the set point affect in a different way the standard house (SM) and the dynamic house (DYN)?

8.5.1 Winter study case

For this study case, we take the south orientation as example and we model four different scenarios: they have the same conditions, except for the set point range of the temperature inside the living zone. We change the minimum temperature set point from 18 to 21°C, with a step of 1°C. For sake of clarity, we focus on four scenarios: scenario 1: $21 - 25°C$, scenario 2: $20 - 25°C$,scenario 3: $19 - 25°C$ and scenario 4: $18 - 25°C$.
At a first look to Figure 8.14, it seems that the SM unit is more sensible to temperature variations than the DYN unit. If the SM user is willing to accept a minimum temperature set point of 18 instead of 21°C, he can save 0.46 $ in two days. By doing the same, the DYN user will save 0.10 $. Nevertheless, if we consider that the DYN model has much lower energy costs than the SM and we normalize the savings, we find that the DYN user is saving 33% on his electricity bill, but the SM user only 24.5%. In other words, user's will weigh more in DYN units.

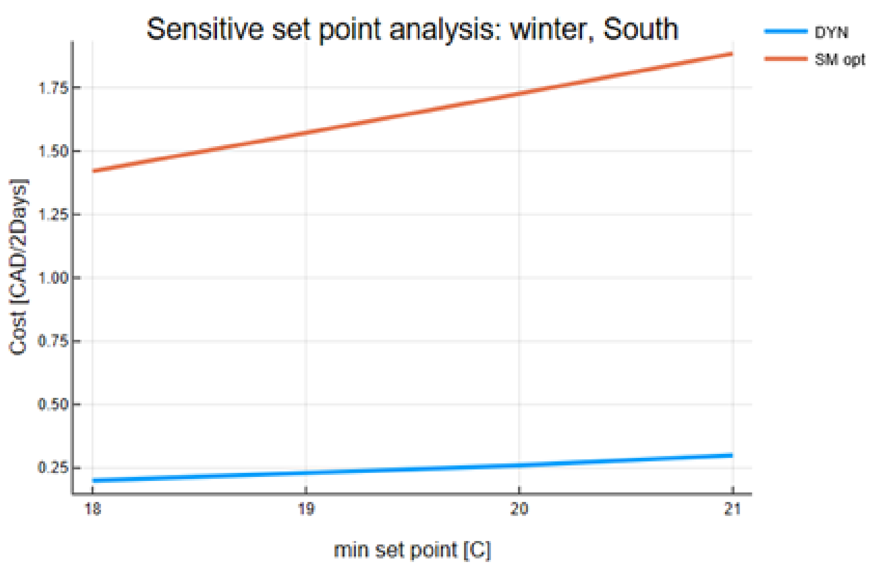

Figure 8.14 Cost variation according to the minimum temperature set point for south oriented DYN and SM units, during winter

8.5.2 Summer study case

We keep studying the south oriented unit as example: the SM and DYN units still run under the same conditions, except for the set point range of the temperature inside the living zone. We change the maximum temperature set point from 22 to 25°C, with a step of 1°C. We focus on four scenarios: scenario 1: $21 - 25°C$, scenario 2: $21 - 24°C$,scenario 3: $21 - 23°C$ and scenario 4: $21 - 22°C$.

As it happened for the winter study case, both the models achieve interesting advantages in shifting their comfort temperature range. The SM user willing to pass from scenario 4 to scenario 1, can save 0.63 $ during two summer days, which means that his final bill is 9% cheaper. Nevertheless, if the DYN user does the same, he saves 0.14 $, so his bill is 13% cheaper.

Both the summer and winter study cases confirm the appeal of the DYN model. In fact, the technology itself together with a conscious behaviour on behalf of his user, represents an interesting strategy to improve the energy efficiency of a city district.

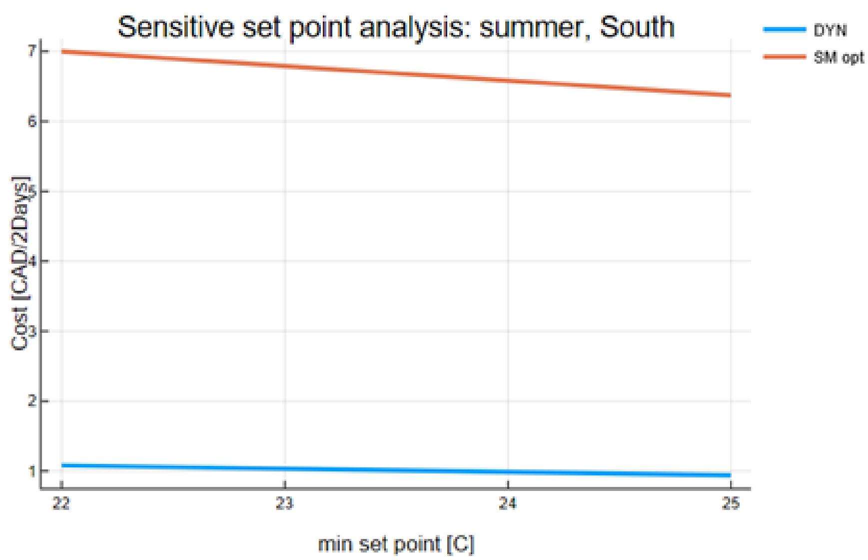

Figure 8.15 Cost variation according to the minimum temperature set point for south oriented DYN and SM units, during winter

CHAPTER 9 CONCLUSION

9.1 Summary of our contributions

The aim of this work was to propose models to minimize the final energy cost and the consumption of a residential/commercial/institutional unit. In addition to that, we wanted to achieve this purpose by profiting from the dwelling's structure itself, without adding expensive additional tools, with the aim to propose an affordable technology. Moreover, we make the models be able to adapt to the different orientations, the dynamic nature of the weather and the user's will.
Specifically, we presented three models: the standard house (SM), the Passive house (PH) and the Passive house with a dynamic façade (DYN).
In the SM, we use the living zone itself as thermal storage: we minimize the final electricity cost by heating the space when the energy price is lower. In this case, we model the technical building features that are the most common in Canada: even if the quality of building insulation is quite poor, thanks to the minimization model proposed, we obtained important reduction in cost.
In the PH, we improve the building insulation and the thermal storage system of the SM model by adding an external additional skin to obtain a double façade system. By doing that, we managed to obtain a drastic reduction in both cost and consumption: for example, the user who lives in a PH with and external wall on the North, has an electricity bill at the end of two winter days that is 80% cheaper than the one of his neighbour, having a Standard house under the same orientation and activity conditions. During summer, he has a electricity bill roughly similar with respect to the user inside the SM. We showed that the PH model brings important advantages during winter and that, during summer, the high temperature inside the storage do not penalize the unit. During winter the PH model does not only minimize cost and consumption, but it also reduces the power peak demand. Because of that, it represents an interesting advantage for the grid operator.
In the Dynamic façade model, we propose and additional improvement of the initial system, by implementing an automated controlled blinds in the double skin. This adaptive shadings are able to manage the amount of solar gains captured by the unit. By doing that, it brings advantages to both the Utility and the user. It reduces the high power peaks in the fluctuating demand and the final cost (as an example, the Dynamic East unit is 41% cheaper than the traditional house) while increasing the internal comfort (visual and thermal). Moreover, we tested the three models in several scenarios, to analyse and answer to some interesting

questions. These are the main contributions of this study:

- We have presented three models to reduce the final electricity cost, while keeping an high quality of comfort. As a consequence, we noticed that also the energy consumption decreased, especially with the PH model during winter and the DYN model during summer. We point out that the systems presented are not only load calculator but they optimize their cost and timing to find the minimum consumption.

- All the models have their thermal storage integrated into the unit is structure: they do not require additional space nor tools. This issue makes the models more affordable for the standard user.

- All the three models mostly have lower energy costs than a traditional house. Thanks to the implementation of the different concepts, we are able to lower the final electricity cost by 80 %.

- It is necessary to account for the orientation, the climate and the activity inside the unit to calculate and optimize its energy demand.

- The Dynamic façade is a significant tool to reduce the demand fluctuation (utility side). The higher is the amount of solar gains captured by the city, the greater is the benefit brought from this technology. Even in a cold city like Montreal, the DYN model brings important benefit to both the user and grid operator.

- The user's habits are important for computing the final cost. Moreover, DYN and PH models can achieve even lower costs by shifting the temperature set point inside the living zone. During winter, for the user living in a standard house (SM) on the south, moving the internal temperature set point from $21 - 25°C$ to $18 - 25°C$ makes the user save the 24.5% in his two-days energy bill. For the user of a Passive house (PH or DYN), it is 33%. During summer, the adaptability of the user impacts less the final bill. If the SM user moves from $21 - 22°C$ to $21 - 25°C$, at the end of two summer days he can save 9%. If the DYN user does the same, his bill will be 13% lower.

The models presented in this study have appeal for industry. As we said, there are several software companies working to implement systems to compute and simulate the energy loads: the capability to minimize this energy needs is an added important value, which will make these software programs be attractive not only for engineers but also for the user. As a matter of fact, because of them, the user can influence the amount of his final energy expense while avoiding to act manually on the system. Furthermore, the more users adopt these models, the easier the operation of the power system becomes. The operator could predict the energy loads (amount and timing) to allocate for the units and he can also reduce the demand fluctuation by connecting the dwellings and sharing, optimally, the energy among them. More in detail, they can take advantage from the different orientation and type of units: their energy loads differ in both amount and timing.

9.2 Future work

9.2.1 Multilayer system

The study presented in this work is part of a larger project: it represents the Layer 1 of what we have called "Multilayer system", which will be completed during my doctoral studies. In particular, the output from this work, will become the input parameter for the optimization problem of the Layer 2. Here, the intent is to manage, optimally, the needs of several connected units, belonging to the same large building. It is important to point out that those units will allocate different activities (for example, they can be household or classrooms) and they will capture diverse amount of solar gains, during various hours: from the full point of view of the building operator, each unit represents a node in a micro-power grid (i.e the building), which has a demand but also a production to deal with. In addition to that, the building will have several energy resources, renewable and not, as pv-panels and electrical vehicles: all of them have to be connected and integrated to the units' loads. To complete the Multilayer system, the larger layer is the city district (layer 3). At this scale, we will take the point of view of the Utility: the goal will be to minimize the operation cost by managing in an optimal way those loads that have been found in Layer 2.
The main challenges of this study are connected to the size of the entire problem. As we said previously, machine learning techniques can be an interesting way to face this issue. In fact, it can be applied to pass from the first to the second layer of the Multilayer system.

9.2.2 Optimal control theory applied to the ventilation inside the double skin

Coming back to the Layer 1, object of this work, to analyse further the ventilation inside the double façade is an interesting future work. In fact, along our study, we have found the importance of this aspect for the final cost and the internal comfort. As we already mentioned, it is interesting to re-model the PH and the Dynamic systems as optimal control problems to manage the mechanical ventilation: the control function should be associated to the openings, which connect the outside to the thermal storage and the thermal storage to the living zone. By doing this, the action to open or close these apertures, is linked to the purpose of obtaining the minimum final energy cost, but also to the comfort inside the living zone.

9.2.3 Glare control

The glare control implementation related to the Dynamic façade model is a relevant topic for future studies. We propose a way to account for the shading changes due to the visual comfort inside the unit: by converting the value d_i^L from a parameter to a variable. In fact, we suggest to represent this variable as a sum of two components, one constant and another that can vary. The last one, which is linked to the status of the blinds, represents an issue to research; it can be calculated by software or algorithms, as Gonzales and Fiorito suggested in [51], designed to calculate daylight metrics but still have some limits, as the simplified geometry of the building.
Accordingly, the following equation becomes a new constraint:

$$d_i^L = d_i^{L,0} + \tilde{d_i^L} \quad \forall i \in I/\{1\} \tag{9.1}$$

Where $d_i^{L,0}$ is the nominal value (a parameter for the model) related to the lighting demand of the unit and $\tilde{d_i^L}$ is the variable linked to the actual condition of the blinds. By doing in this way, we could enter all the details related to the technical features of the blinds (for example, its thickness) and its status (i.e opened or closed). If the unit is very large or if there are different activities inside, maybe performed in different zones (something closer to the windows than others), it could be interesting to divide the full façade's surface in smaller parts and to connect one variable $\tilde{d_i^L}$ to each of them. In that sense we would have k-parts of the full windows surface.

$$d_i^L = d_i^{L,0} + \sum_{k=1}^{K} \tilde{d_{i,k}^L} \quad \forall i \in I/\{1\} \tag{9.2}$$

It is necessary to point out that, if the unit has this type of dynamic behaviour, also its blinds should be able to partially close. Furthermore, if we think deeper about the shading behaviour to avoid glare, we will realize that the discomfort is strictly linked to the *amount and direction* of the direct solar gains component. This means that we could profit from that by having what we can call "solar shading" : instead of having a standard blinds, we could implement solar panels which not only shade the excessive sun rays, but also capture their energy.

Solar shading: glare control improvement

The glare control topic can be farther developed: we suggest to implement a dynamic shading model that has solar panels on its surface. By doing this, it would be possible not only to improve visual comfort, but also to capture some extra energy. Furthermore, the resulting model could merge two important fields: the daylight design and cost minimization. In fact, we have reason to say that, even if the research about the daylight design is spreading, it is difficult to find in the Literature works which integrate comfort needs to cost (and consumption) minimization. As Fiorito and other researchers well summarized in their work [49], the studies of solar shadings are going toward the topics of bio-mimetic principles and smart materials. More in detail, they are studying a way to make the shadings as natural and cheap as possible, by analysing elastics reversible movements or smart components as memory shape materials. Until now, it seems to be that the main goal is to improve the user comfort; however, we have reason to say that it could be interesting to integrate this purpose to environment consideration. To do that, the models proposed in our work can be integrated into the field of daylight design; moreover, other smart elements can be implemented, as the *Self healing materials* that Salerno analysed in her thesis [52]: the dynamic façade will benefit from their great durability and their ability to heal by themselves after small damages, reducing maintenance cost.

User's response

The user's behaviour always represents a limit, in a certain way, for automatic systems. It has been shown [49] that the efficiency of the process is strictly linked to their interaction with the automated system. In addition to that, occupants usually have low tolerance for changes, especially if they are out of their control. Because of these reasons, it is necessary to study user's reaction to those models, before implementing them as prototypes.

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ANNEXE A PROGRAMMING CODE EXAMPLE

During this work, different models have been coded by using Julia programming language. More in detail, we write 6 different models for the SM, PH and Dynamic PH systems, where each of them has the winter and the summer cases. Moreover, each system runs with 4 data files which represent the 4 orientations South, East, West and North. These data files are different for each system and for the winter and summer cases, for a total of 24 data files. In addition to that, we wrote and run other models to make the sensitivity analysis presented in the chapter **"Results analysis"** .

For the sake of simplicity, we attached to this thesis only one representative model: the summer study case of the DYN system.

```
using JuMP
using Cbc

# function f(uS)
m = JuMP.Model(solver=CbcSolver())

#set timeframes frame

#Decisional variables
@variable(m, Q_HU[i=1:timeframes] >= 0)
@variable(m, Q_HS[i=1:timeframes] >= 0)
@variable(m, Q_CU[i=1:timeframes] >= 0)
@variable(m, Q_CS[i=1:timeframes] >= 0)
@variable(m, 21 <= T_intU[i=1:timeframes] <= 25)
@variable(m, -10 <= T_intS[i=1:timeframes] <= 43)

#Other variables
@variable(m, Q_veU[i=1:timeframes])
@variable(m, Q_veS[i=1:timeframes])
@variable(m, Q_room[i=1:timeframes] )
@variable(m, Q_store[i=1:timeframes] )
@variable(m, Q_wall[i=1:timeframes] )
@variable(m, T_wall[i=1:timeframes])
@variable(m, q_sol[i=1:timeframes])
@variable(m, Q_Ctot[i=1:timeframes])
@variable(m, Q_Htot[i=1:timeframes])
@variable(m, WQ_Ctot[i=1:timeframes])
@variable(m, 0.3 <= delta[i=1:timeframes] <= 1)
@variable(m, x[i=1:timeframes], category = :Bin)
@variable(m, Q_Ls[i=1:timeframes] >= 0)
@variable(m, D[i=1:timeframes] >= 0)
@variable(m, W_C[i=1:timeframes] >= 0)


#constraints
#Energy balance
 for i in 1:timeframes
     #node1
     @constraint(m, - (a_op/((r_wall/2) + r_in))*(T_wall[i] - T_intU[i]) - Q_wall[i] - ((a_op/((r_wall/2) + r_in))*(T_wall[i] - T_intS[i])) == 0)

     #node2
     @constraint(m, -((a_w*uU_w)*(T_intU[i] - T_intS[i])) + Q_HU[i] - Q_CU[i] + q_int[i] + q_sol[i] + alfa_w*q_inf[i] + Q_veU[i] -
                    - Q_room[i] - ((a_op/((r_wall/2) + r_in))*(T_intU[i] - T_wall[i])) - D[i] == 0)
     #node3
     @constraint(m, - Q_store[i] - (a_op/((r_wall/2) + r_in))*(T_intS[i] - T_wall[i]) + Q_HS[i] - Q_CS[i] + gamma*q_sol[i] +
                    + Q_veS[i] - (a_S*(uS + (1/r_0))*(T_intS[i] - t_ext[i])) + D[i] == 0)

#Ventilation
 @constraint(m, Q_veS[i] == ((1- beta)/100)*(m_air)*cp_air*(t_ext[i] - T_intS[i]))
 @constraint(m, Q_veU[i] == ((1- beta)/100)*m_air*cp_air*(t_ext[i] - T_intU[i]))

#Power capacity and system efficiency
 @constraint(m, Q_HU[i] + Q_HS[i] == Q_Htot[i])
 @constraint(m, Q_CU[i] + Q_CS[i] == Q_Ctot[i])
```

```
 @constraint(m, WQ_Htot[i] == Q_Htot[i]/1)
 @constraint(m, WQ_Ctot[i] == Q_Ctot[i]/1)
 @constraint(m, WQ_Htot[i] <= p)
 @constraint(m, WQ_Ctot[i] <= p)

#Temperature limits
 #Living zone
  if i == 1
  @constraint(m, T_intU[i] - T_intU0 <= 3)
  else
  @constraint(m, T_intU[i] - T_intU[i-1] <= 3)
  end
  if i == 1
  @constraint(m, T_intU0 - T_intU[i] <= 3)
  else
  @constraint(m, T_intU[i-1] - T_intU[i] <= 3)
  end

 #Storage
  if i == 1
  @constraint(m, T_intS[i] - T_intS0 <= 10)
  else
  @constraint(m, T_intS[i] - T_intS[i-1] <= 10)
  end
  if i == 1
  @constraint(m, T_intS0 - T_intS[i] <= 10)
  else
  @constraint(m, T_intS[i-1] - T_intS[i] <= 10)
  end

#Weather condition
 @constraint(m, q_sol[i] == 1*delta[i]*(q_solB[i] + q_solD[i]))      #cl index_summer=1

#lighting
 delta0 = 1
  if i == 1
  @constraint(m, delta[i] - delta0 <= x[i])
  else
  @constraint(m, delta[i] - delta[i-1] <= x[i])
  end

  if i == 1
  @constraint(m, - delta[i] + delta0 <= x[i])
  else
  @constraint(m, - delta[i] + delta[i-1] <= x[i])
  end

  @constraint(m, Q_Ls[i] == x[i]*0.18 + d_Ls[i])
```